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AN ANCIENT GLACIAL FORMATION IN UTAH

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ABSTRACT

In the Wasatch Mountains and on several of the islands in Great Salt Lake, Utah, there are outcrops of rocks which are believed to be of glacial origin and are probably parts of a single widespread formation. They comprise tillite, fluvial conglomerate, varved slate, and graywacke. The tillite is over 300 feet thick and contains boulders as much as 20 feet long. A few of the erratics are striated. The varved slates are much thicker, and some of the beds contain scattered pebbles thought to have been dropped by floating ice. The formation has yielded no fossils, but it underlies Cambrian terranes, in several places disconformably but in others perhaps conformably. Like the Paleozoic strata, it has suffered strong folding but not much metamorphism.

INTRODUCTION

Among the many interesting stratigraphic problems of the Salt Lake basin in Utah, that of the ancient tillites and glaciofluvial deposits of early Cambrian or perhaps pre-Cambrian age is one that merits more consideration than it has yet received. Having studied these strata at intervals during the seasons of 1909, 1923, and 1924, it was my expectation to continue the work until a satisfactory understanding of them might be attained. As other interests have since crowded the project aside, it now seems best to publish the results already gained, lest they become stale and eventually lost.

The map (Fig. 1) shows the distribution of the tillites as far as known to me. They were first observed by Captain Stansbury[1] in 1849, although he had no suspicion of their origin. It is rather strange that, aside from a reference to slates and conglomerates

[1] H. Stansbury, "Exploration and Survey of the Valley of the Great Salt Lake of Utah, etc.," *U.S. 32d Congr. Spec. Sess., Sem. Ex. Doc. 3* (1853).

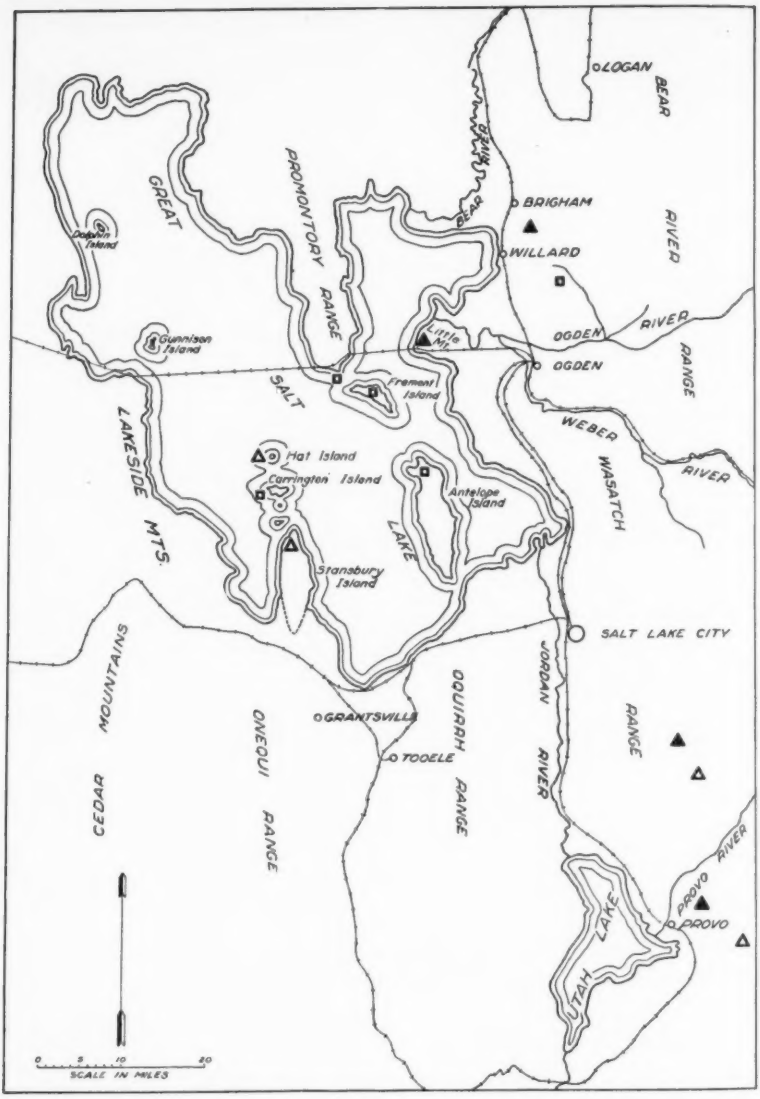

FIG. 1.—Map of Great Salt Lake and vicinity, showing localities at which the ancient glacial formation has been found or is suspected of occurring.

▲ Localities studied by the author.
△ Localities where tillite has been found by others.
▫ Other suspected occurrences of the glacial formation.

on Carrington and Hat islands, Emmons[1] and Hague, in the report of the Fortieth Parallel Survey, scarcely mention this formation. In fact, Captain Stansbury, although an engineer rather than a geologist, gave more information regarding the geology of the islands in Great Salt Lake than the much later expedition which was expressly geologic in its organization and purpose.

It was not until 1913 that Hintze[2] announced the opinion that the boulder slate in Big Cottonwood Canyon is probably of glacial origin.[3] Some years later (1924) I discussed the subject at a meeting of the Geological Society of America.[4]

There is so much diversity in the widely scattered occurrences of these glacial formations that it seems best to describe them in such detail as available information now permits, beginning with the locality which seems to be the best known, if not the most promising. After the facts have thus been set forth, a more general commentary may be made.

DESCRIPTION BY LOCALITIES

LITTLE MOUNTAIN

The group of hills known as Little Mountain forms the shore of Great Salt Lake about 14 miles west of Ogden.[5] The sketch map (Fig. 2), which was made by the rather crude pace-and-compass method, serves to show the general relations. The hills are relatively bare, and outcrops plentiful. Gravel bars and the tufa deposits of ancient Lake Bonneville obscure them only locally.

Little Mountain consists largely of massive tillite of such declared characteristics that I first recognized it tentatively from the window of a passing train. It is a hard blackish gray argillite or slate containing scattered boulders and smaller blocks of all sizes up to a maximum of about 9×5×4 feet. Angular blocks are rare, and although well-rounded cobbles are not uncommon the great majority are subangular. Many are definitely soled or faceted. Striae, pre-

[1] S. F. Emmons, *U.S. Geol. Surv. Report, 40th Par.*, Vol. II (1877), p. 461.

[2] He credits F. J. Pack with the suggestion.

[3] F. F. Hintze, "A Contribution to the Geology of the Wasatch Mountains, Utah," *Ann. N.Y. Acad. Sci.*, Vol. XXIII (1913), pp. 85–143.

[4] Eliot Blackwelder, *Geol. Soc. Amer. Bull.*, Vol. XXXVI (1925), pp. 132–33.

[5] In the northeast quarter of T. 6 N., R. 4 W. and the NW. ¼ of T. 3 W., R. 6 N.

sumably glacial, were found on only a few stones; but the rarity of such finds is not surprising in view of the fact that as a result of metamorphism the matrix generally adheres tightly to the blocks and cannot be separated from them. There is no trace of stratification or assortment of material in the mass. Microscopic study (Fig. 5) shows that the matrix is a heterogeneous mixture of fresh particles of many rocks and minerals of all sizes. Much of it was originally a black silt. Among the constituents, angular bits of feldspars, quartz, biotite, and other micas are readily identified, along with particles of magnetite (?) and black slate. The pebbles and boulders consist largely of flesh-colored gneissoid granite and white and gray metaquartzites.[1] There are also a few boulders of hornblende gneiss, brown mica-schist, laminated gray dolomites, and a peculiar bright green metaquartzite. Of these the white and green metaquartzites occur in the pre-Cambrian formations of the Wasatch range, southeast of Brigham, Utah,[2] but the rest are of unknown derivation.

FIG. 2.—Sketch map of Little Mountain, west of Ogden, Utah. The symbols represent rock outcrops as follows: *A*, tillite; *B*, lava; *C*, striped slate member.

Although the tillite has suffered incipient metamorphism, it is apparently not much recrystallized. Rude slaty cleavage, at a rather constant dip of about 30° west, is prevalent. In some places this cleavage is obscure, and the rock appears relatively massive.

[1] Recrystallized quartzite.

[2] Blackwelder, *op. cit.*

FIG. 3.—Cliff of slaty tillite near the southwest corner of Little Mountain, west of Ogden. The camera was facing northward.

FIG. 4.—Slaty tillite containing subangular boulders of quartzite. Little Mountain, west of Ogden. (The Brunton compass used as a scale is about 3 inches wide.)

At two points,[1] beds of fluvial conglomerate and stratified graywacke 2–3 feet thick are included in the tillite.

Beneath the tillite, in the southeast part of the hills, a series of slates is well exposed in railroad cuts. The rocks are finely and very

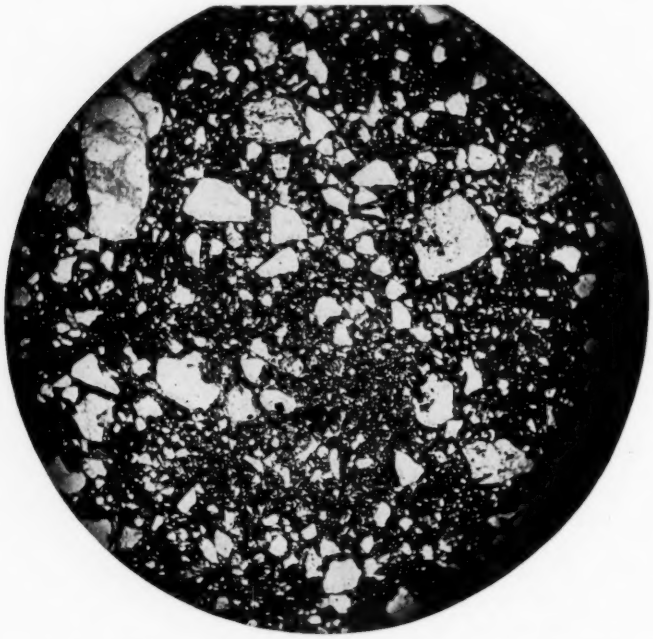

FIG. 5.—Microphotograph of the matrix of the tillite from Little Mountain. The angular fragments consist of metaquartzite and granite. (Magnification, ×20.)

evenly laminated, or varved (see Fig. 6), in thicknesses of $\frac{1}{2}$–3 millimeters, varying in color from silvery to dark smoky gray. The stratification is similar in character to that found in glacial lakes. Secondary pyrite cubes, as much as 5–20 millimeters in diameter, are common in certain zones. In the upper part of the slaty sequence a few thin beds of massive hard graywacke—the thickest only 3 feet—are interbedded with the slate.

[1] Near the north and the southwest corners.

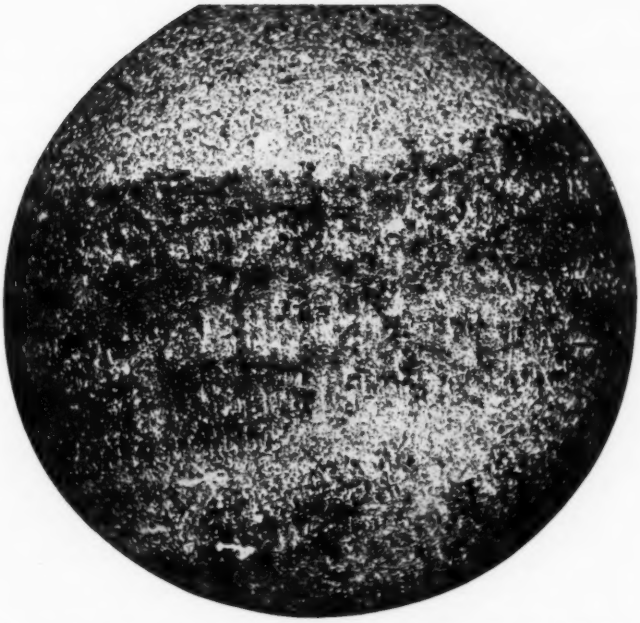

FIG. 6.—Microphotograph of varved slate from Little Mountain, Utah. The middle of the circle is crossed by one of the fine-grained laminae which was probably clay before metamorphism. On either side are coarser light-colored bands of silty texture. Magnification, ×20.)

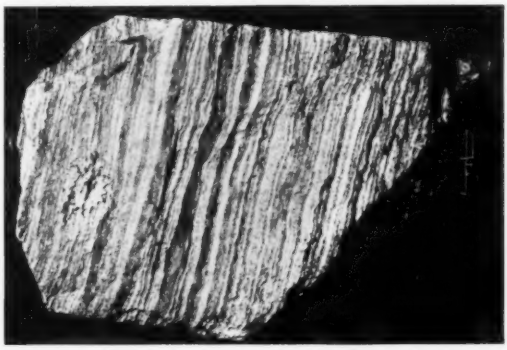

FIG. 7.—Photograph of a specimen of gray varved slate from the southeastern part of Little Mountain. The individual laminae average 1–2 millimeters in thickness.

Almost at the top of the slaty series a greenish amygdaloidal lava flow has similar relations. This rock is badly altered but still shows abundant plagioclase crystals. Secondary calcite, chlorite, and leucoxene are probably derivatives of pyroxene and other original minerals. The rock may well have been a diabase.

The formations in Little Mountain appear to lie in a gentle syncline, followed on the southeast by an anticline. Outcrop relations suggest a fault striking westerly and dropping the tillite several hundred feet on the north. The slates are estimated to be over 600

FIG. 8.—Photograph of a specimen of tillite from Little Mountain. An isolated pebble of granite is shown near the left end. (Specimen 10 inches long.)

feet thick. Owing to the scarcity of definite strata in the tillite, its dimensions are much less certain, but the thickness is probably not less than 300 feet.

THREE-MILE CANYON

On the west front of the Wasatch Mountains, about 3 miles southeast of Brigham, glacial beds are again well exposed in the ravine locally known as Three-Mile Canyon, about $\frac{2}{3}$–$1\frac{1}{2}$ miles east of the range front. The exposures are not continuous, and the structure is sufficiently complex that the stratigraphy is only imperfectly known. Concealed faults are suspected.

At least one bed of tillite about 300 feet thick is present. It is a dark gray massive rock, sprinkled at random with pebbles and boulders up to 4 feet in length. The constituents are gneissoid

granite (about 60 per cent), white and gray metaquartzite (about 35 per cent), and vein quartz and buff dolomite or marble (about 5 per cent). The rock is unstratified but has obscure slaty cleavage. Although many pebbles showed facets and suggestive forms, none with definite striae were observed.

The tillite is overlain, apparently conformably, by about 200 feet of dark gray slate which weathers to a dull olive color. Part of this member is finely laminated or varved, but most of it is not. It contains a few interstratified thin layers of graywacke. The slaty beds grade upward into light gray quartzite, tinged with olive, which seems to be continuous above with the great sequence of Middle Cambrian and probably Lower Cambrian quartzites and shales that form the range east and southeast of Brigham. This series is believed to be over 5,000 and is probably at least 8,000 feet thick, but the stratigraphy has been only incompletely worked out.

Below the tillite, relations are more obscure. Only accurate detailed mapping will suffice to make them known. The nearest underlying bed is a striped gray slate. Others apparently associated nearby are silvery gray slates, varved (or banded) like those in Little Mountain, gray arkose or graywacke, finely laminated clay slate, black and gray silty and clay slates containing pyrite cubes, and massive graywacke with beds of fine conglomerate. One of the varved gray slate beds contains scattered pebbles like those in the tillite and resembles a well-known type of glaciolacustrine deposit. The varved strata below the tillite appear to be only a few hundred feet thick, but no definite base has been found. A detailed study of this locality will doubtless yield more information regarding the true position of the glacial formation in the stratigraphic column, for the entire sequence may be present, although greatly complicated by folding and faulting.

BIG COTTONWOOD CANYON

In Big Cottonwood Canyon, southeast of Salt Lake City, a bed of tillite crosses the main road about 1 mile below the old Maxfield Mine (or about 6 miles east of the mouth of the canyon). The rock is not well exposed and its relations are obscure. For this bed Hintze[1] suggested a glacial origin and tentatively a correlation with the mid-

[1] *Op. cit.*, pp. 100–101.

Proterozoic Cobalt tillite of Ontario, Canada. He found no striated boulders. According to Hintze, the tillite has been traced southward as far as the canyon of American Fork, some 9 miles. In his report on the glaciation of the Wasatch range, Atwood[1] gives a good photograph of an outcrop of this formation in Little Cottonwood Canyon, but makes no mention of it in the text.

FIG. 9.—Photograph of slaty tillite near the mouth of Rock Canyon (north side), northeast of Provo, Utah.

ROCK CANYON

Just northeast of the city of Provo, the lower part of Rock Canyon affords an excellent exposure[2] of tillite just below the great cliff of Cambrian buff quartzite. It is a massive rock of medium gray color tinged with olive and therefore of a distinctly lighter hue than the tillite at Little Mountain. It shows no trace of bedding, but contains scattered pebbles and boulders. Blocks 1–10 inches in diameter are abundant, those 2–4 feet thick are not rare, and the largest block observed measures 11×19 feet, although only partly exposed.

[1] W. W. Atwood, *U.S. Geol. Surv. Prof. Paper 61* (1909), p. 80.

[2] For guidance to this locality I was indebted to Professor Fred Buss, then residing in Provo.

Most of the boulders are subangular, some are well rounded, but none are sharply angular. A few show distinct facets, but, as in the other localities already mentioned, the matrix adheres so tenaciously to the boulders that no original surfaces could be clearly examined for striae. Only suggestions of grooves were observed. The matrix has been so heavily compressed that the pebbles now occupy eye-spots and slaty cleavage is well developed. Recrystallization of the more susceptible parts of the matrix into a finely micaceous slate has made notable progress.

The boulders in the tillite consist of rocks which are similar to, if not identical with, those at Little Mountain, although present in very different proportions, as follows:

	Per Cent
Dense gray dolomites, some of which are finely laminated. With these there is more or less black chert	about 55
Metaquartzites of white, brown, and dull gray colors	about 50
Miscellaneous rocks, including chloritic and sericitic phyllites, hornblende schist, and gneissic granitoid rocks	about 5

The base of the tillite is not exposed, but the upper limit is clearly visible. The buff white Cambrian quartzite, which here appears to be less than 1,000 feet thick, rests in sharp contact on the tillite. The latter shows but little evidence of decay. The basal layer of the quartzite is gritty and coarse, but contains very few pebbles. The contact appears to be a disconformity.

Professor Buss informs me that the tillite outcrop has been traced northward only a short distance from Rock Creek but southeastward beyond Slide Canyon. Its character and stratigraphic position remain unchanged throughout that strip.

LANDING ROCKS

At this point, which lies between Fremont Island and Little Mountain, Stansbury[1] found "slate lying beside a dark rock filled with pebbles and stones as large as a man's head, consisting of what appeared to me to be granite." Locally it contained pyrite cubes and "boulders of feldspathic rock." The resemblance of this formation to that at Little Mountain is apparent.

[1] *Op. cit.*, p. 164.

FREMONT ISLAND

In describing this island Stansbury[1] notes the occurrence of soft slate in which the laminae are "regular, parallel and quite thin." It contains cubes of pyrite. With it is associated a massive hard rock in which are imbedded "stones and pebbles of quartz and granite." From this I suspect the presence of the tillite and varved slate of Little Mountain, which lies not far to the north.

HAT ISLAND

This low rocky islet in Great Salt Lake and about 12 miles southwest of Promontory Point is distinguished chiefly for the countless gulls and pelicans which use it as a nesting haven. Stansbury[2] reported it to be "merely a pile of granitic conglomerate." Dr. W. C. Allee,[3] who made a zoölogic visit to the island in July, 1924, kindly brought me several photographs and specimens of the prevailing rock. These reveal all the usual characteristics of the tillite at Little Mountain—a structureless dark gray argillite containing scattered pebbles and boulders of gneissic granite and metaquartzite.

CARRINGTON ISLAND

From Stansbury's report[4] I infer that the slates, which elsewhere form part of the glacial series, occur there, for he mentions "excellent roofing slate," laminate and containing cubes of pyrite. This strongly suggests the varved slates at Little Mountain.

DOLPHIN ISLAND

Stansbury's[5] mention of conglomerate as occurring on this island is only a hint that may lead to the discovery of tillite there also.

STANSBURY ISLAND

Beyond a reference to "conglomerates" in Stansbury's report[6] and the mention by Hintze[7] of a bouldery rock supposed by Pack to be of glacial origin, I have no information regarding the occurrence of the glacial formation upon this large and little-known island or peninsula in the southwestern part of the lake.

[1] *Ibid.*, pp. 159, 163.
[2] *Ibid.*, p. 162.
[3] University of Chicago.
[4] *Op. cit.*, p. 161.
[5] *Ibid.*, p. 190.
[6] *Ibid.*, p. 170.
[7] *Op. cit.*, p. 100.

PROMONTORY POINT

About 1 mile west and south of the railroad station a well-exposed section reveals several hundred feet of gray slate and quartzite that strongly suggest the early Cambrian strata southeast of Brigham. Many of the slates are finely laminar, like the varved clays of Pleistocene glacial lake deposits. In this locality, however, I saw no tillite and no pebbly slates such as those near Brigham. Their relation to the glacial formation is problematical.

GENERAL DISCUSSION

Although there is considerable diversity among the various occurrences of these presumably glacial rocks, certain facts about them are of rather general application.

The most notable and widespread type has been referred to in this paper as "tillite." It is usually a sooty gray rock, without bedding or assortment of its components. The matrix is a gritty argillite in which the microscope shows (Fig. 5) a heterogeneous mixture of angular grains of rock, feldspar, quartz, and other minerals inclosed in a blackish paste in which micas can be recognized. All the minerals are fresh and unstained. Rather sparsely, but wholly at random, boulders and smaller particles are scattered through this mass. The largest are blocks 10–20 feet in diameter. Many are 3–5 feet in length. For the most part they are neither angular nor round but intermediate in form. Although many kinds of rocks are represented in the boulders, a flesh-colored gneissic granite and white or grayish metaquartzite generally predominate. In one locality (near Provo), dolomites replace the granite in importance. The metaquartzites—especially the vivid green variety—are identical with certain members of the metaquartzite and muscovite-schist series of the Wasatch Mountains,[1] a metamorphosed sedimentary formation of early pre-Cambrian age. Gneisses and schists also occur in the Wasatch Mountains northeast of Ogden. The other components of the tillite have not been related to any rocks known in place, but all are metamorphic and may well belong to the same general system as the metaquartzites. It is significant that no material resembling the slates and quartzites of the late pre-Cambrian (Belt or Grand

[1] Best exposed on the north slope of Willard Canyon (Blackwelder, *op. cit.*, p. 131).

Canyon) system has been found in the tillite, although some 12,000 feet of these beds underlie the tillite in Big Cottonwood Canyon.

So far as known there is only one bed of tillite in each locality, but that bed is thick—certainly 300 feet in some places and probably more. In most localities the full thickness is not exposed.

Associated with the tillite in several of the localities there are other rocks of interest. Occasional lenses of stratified conglomerate and coarse graywacke are included within the tillite mass. Strata of like stratification and degree of assortment are also common in Pleistocene tills and are known to be of fluvial origin.

Much thicker formations consist of slates, among which finely banded gray varieties predominate. They closely resemble the varved clays and silts that accompany the glacial deposits of recent times. In some of the striped slates there are widely scattered pebbles and small boulders which may well have been dropped by icebergs floating in the glacial lakes. The microscope shows that the slates have much the same composition as the tillite except that the particles are fairly well sorted. Among the slates one finds thin beds of graywacke and fine conglomerate which closely resemble the sandy and gravelly deposits made near the borders of modern glaciers.

A unique member of the glacial series at Little Mountain is a thick lava flow, originally vesicular and probably of diabasic composition. It lies just below the massive tillite and appears to have been due to a contemporaneous outflow.

The stratigraphy of the glacial series is not yet well known, nor indeed is it the same in all places. In the southern part of the Wasatch Range, the tillite lies just below the mid-Cambrian quartzite and is not known to be accompanied by any striped slates. Near Ogden and Brigham, however, the striped slates underlie the tillite and in the latter place also lie above it. Even the lower slates may be over 600 feet thick.

In nearly all the localities the rocks have been slightly metamorphosed. Slaty cleavage is prevalent but generally not intensely developed. The microscope shows that part of the slates and of the matrix of the tillite have recrystallized, forming micas and other secondary minerals, but the sand grains, pebbles, and boulders are

practically unchanged. The incipient recrystallization has had the effect of cementing the matrix so tightly to the boulders that it cannot be disengaged from them, and hence it effectually conceals such striated surfaces as they originally had.

By way of justifying my use of the term "tillite," with its implication of glacial origin, it may be said that the deposits have many distinctively glacial features. In a few cases soled or faceted pebbles, with parallel grooves and scratches still visible on them, have been found in the tillite. The striped slates with pebbles sprinkled at random are equally significant. The matrix of the tillite and the great mass of wholly unstratified débris are such as are characteristically formed by glaciation and cannot, I believe, be made by any other process except mudflow or landslide action. Therefore, I conclude that the glacial origin of these rocks is quite as credible as that of most other ancient glacial formations, such as those at Squantum in Massachusetts, and Cobalt in Ontario.

The age of the glacial series is not yet definitely known. It must be younger than the metamorphic pre-Cambrian system from the erosion of which it was largely derived. It must also be older than the buff quartzite, which from Willard southward forms the base of the Paleozoic system. That quartzite is commonly regarded as of Middle Cambrian age. The plainly disconformable contact at the top of the tillite near Provo and in Big Cottonwood Canyon, and the fact that the quartzite rests here upon tillite, there upon gneiss, and elsewhere upon nonglacial slate suggests that there is a noteworthy stratigraphic break between the tillite and the quartzite.

Relations between the tillite and the Cambrian system, above and northeast of the great Willard overthrust[1] in the Wasatch Range, are very different, and in that respect accord with the general rule that the Paleozoic stratigraphy of the two areas is unlike. Near Brigham the tillite and associated pebbly varved slates are interbedded with the lower part of a great sequence of alternating slates and quartzites which become more arenaceous toward the top. The uppermost beds have yielded Middle Cambrian fossils.[2]

[1] Blackwelder, *op. cit.*, Vol. XXI (1910), pp. 517–42, Vol. XXXVI (1925), pp. 132–33.

[2] C. D. Walcott, "Pre-Cambrian Fossiliferous Formations," *Geol. Soc. Amer. Bull.*, Vol. X (1899), pp. 199–244.

The barren slates and quartzites below the lowest fossiliferous zone are thousands of feet thick and their base has not yet been found. Yet the whole series appears to be conformable. One may reasonably infer, therefore, that the lower part of the slate-quartzite series near Brigham, including the tillite, is of Lower Cambrian age.

The fact that no boulders derived from the late pre-Cambrian[1] slates of the central Wasatch region have ever been found in the glacial series may even be taken to indicate that the tillite is but little younger than that system. Under those circumstances the Beltian slates may not have been consolidated or even subject to erosion during the glacial episode.

Meanwhile the only definite conclusion warranted is that the glacial formation is either early Cambrian or late Proterozoic.

In the absence of fossils the correlation of the tillites in the several localities is difficult because the occurrences are all isolated. There is, however, little to suggest that they are not essentially one formation with local variations. In the present state of uncertainty about the stratigraphy and correlation it seems best not to confer a formation name on these beds but to refer to them merely as the ancient glacial rocks of the Great Salt Lake basin.

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A. P. Coleman. *Ice Ages, Recent and Ancient.* New York, 1926. Pp. 289.

[1] Probably Beltian, late Proterozoic system (C. D. Walcott, "Cambrian Sections of the Cordilleran Area," *Smiths. Misc. Coll.*, Vol. LIII, No. 5 [1908]).

POTHOLE EROSION

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ABSTRACT

This study was undertaken for the purpose of determining hypotheses for pothole erosion that could be demonstrated by laboratory experiment. Three types of power circuits, experimentally demonstrated, are used to explain the three types of stream potholes. The bearing of these results on the "moulin" and "grinder" hypotheses is discussed.

INTRODUCTION[1]

Although of secondary geological importance among the results of corrasion, potholes often constitute one of its most interesting and remarkable expressions. The great potholes of the Glacier Garden at Lucerne, Switzerland, have excited the wonder of two generations of travelers. At that place a group of potholes was discovered in 1872 during the process of excavating for a basement in the glacial drift. Later the drift was removed uncovering over thirty holes irregularly grouped in waterworn and striated bedrock. The whole area including the potholes is stated by Upham to be "about eight rods long and four rods wide"[2] and includes holes up to 26 feet in diameter and 31 feet deep. The famous potholes in the Interstate Park at Taylor's Falls, Minnesota, are by all means the outstanding attraction to the thousands of tourists who visit that park annually. Among the holes now cleaned out is one 12 feet in diameter and 60 feet deep. Another having more than twice this diameter has not been emptied. Approximately one hundred holes varying in size from those mentioned above to some 3 inches in diameter and 12 inches deep are to be found in the park or adjacent to it. Potholes are also of great interest as a mode of river erosion. These deep holes bored into the hard rock of stream beds constitute most efficient means for the deepening of channels in resistant rock.

[1] The writer wishes to acknowledge important constructive criticisms received from Dr. C. R. Stauffer, of the geology department of the University of Minnesota, and valuable suggestions from Dr. F. F. Grout, Dr. J. W. Gruner, Dr. G. M. Schwartz, and Dr. G. A. Thiel of the same department.

[2] W. Upham, "Giants' Kettles Eroded by Moulin Torrents," *Bull. Geol. Soc. Amer.*, Vol. XII (1900), p. 40.

TERMINOLOGY

The term "giants' kettles," coined by early observers and commonly used in both Europe and America, can be fittingly applied only to the holes of large size; therefore the word "pothole," which suffers no such restriction, has come to be the more commonly used English term. The general usage of this word, however, to cover a large variety of holes in rocks produced in various ways has robbed it of whatever technical significance it may ever have possessed. Elston, in classifying pothole depressions, includes "plunge pools," "solution potholes," and "potholes due to sea urchins" with what he terms "normal potholes,"[1] which "are developed by the rotary grinding motion imparted to rock tools—sand, pebbles, boulders—in a depression of the bed of a stream course by the water current."[2] Udden has used the term "etched potholes"[3] for depressions formed in limestone by algal growth.

This paper deals particularly with the relatively deep holes or depressions, commonly called "potholes," formed in bedrock by stream action and with the mechanics involved in their production. Such holes are of three types. First: those caused by the rotary or eddying action of water, which, for purposes of clearer distinction, will be termed "eddy holes." A corresponding term, *Strudellöcher*, is commonly used in German. Second: those produced by the more or less oblique direct impact of swift currents in rapids. These holes are literally gouged out and may be termed "gouge holes." Third: those produced by falling water. Wherever the water of a stream passes over a ledge and plunges vertically downward, a hole is eventually eroded into the rock. The pools filling such holes have been called "plunge pools." The holes may be termed "plunge-pool holes."

Although the term "pothole" emphasizes the form of the hole rather than the agent or mode of action of the agent and is a misnomer when applied to many of the cavities that have been discussed under that caption, common usage for years has firmly in-

[1] E. D. Elston, "Potholes: Their Variety, Origin and Significance," *Sci. Monthly*, Vol. V (1917), p. 557.

[2] *Ibid.*, Vol. VI (1918), p. 37.

[3] J. A. Udden, "Etched Potholes," *Tex. Univ. Bull. 2509* (1925).

trenched it in the English vocabulary. It is used in a general sense in this paper to include the three types of holes mentioned above.

EDDY HOLES

Eddy holes may be defined as holes of circular or elliptical cross-section which are worn into the rock of stream beds by sediments whirled by stationary eddies. By a stationary eddy is meant one that acts continuously or occurs intermittently at the same point.

Eddy holes are found in practically all kinds of rocks. In Minnesota along the Kettle River near Sandstone they are found in a compact sandstone which is quarried at that point extensively for building stone. Along the north shore of Lake Superior they are found in and near the channels of many of the swift streams that flow into the lake. The rock host here is mostly basalt. Schwartz recently described a very large one close to a waterfall in Brule (Arrow Head), River.[1] McKellar has described a group of potholes near McKellar Harbor on the north shore of Lake Superior which are eroded in hornblendite.[2] Along the Minnesota River they are found in granite, and in the Interstate Park at Taylor's Falls a most remarkable group occurs in basalt. In Wisconsin some small ones are found in the quartzite on the high bluff on the east side of Devil's Lake. Their occurrence in practically every type of consolidated rock indicates that the nature of the rock is not an important factor in their formation.

While eddy holes vary considerably in shape, the form is in general circular though some are markedly oval or elliptical. The relation of depth to diameter varies through wide limits. Some are several times as wide as deep. In other instances, as at Taylor's Falls, Minnesota, many are several times as deep as wide. The large as well as the small exhibit alike this wide range in the ratio of diameter to depth. In a given hole the diameter may vary considerably at different depths. The "hourglass" at Taylor's Falls contracts from about 36 inches in diameter to about 18 inches and then expands again to nearly 36 inches. The 60-foot hole, the deepest known in this locality, is 12

[1] G. M. Schwartz, *Minn. Geol. Surv. Bull. 20* (1925), p. 84.

[2] P. McKellar, "Potholes North of Lake Superior," *Bull. Geol. Soc. Amer.*, Vol. I (1890), p. 568.

feet in diameter at the top, 15 feet in diameter at a depth of 40 feet, and at the bottom contracts to about 3 feet. In general the cylindrical axis is vertical but in some cases makes a slight angle with the vertical. The axis of the 60-foot hole at Taylor's falls is strongly deflected. Many are fluted or grooved spirally. The mouths of some eddy holes are undercut while the mouths of others are quite widely flaring.

They are generally found in the beds of rapid streams or in abandoned stream channels. Many are found, however, where the presence of a stream at any past time appears difficult to demonstrate. In Norway many appear along the coast near sea level and close to the water edge. Stone describes potholes on the island of Georgetown at the mouth of the Kennebec River.[1] The larger holes and by far the majority of them are found in the regions which have been glaciated.

MOULIN HYPOTHESIS

It appears that from the first scientific observations eddy holes were regarded as the work of whirling water equipped with sediment as grinding tools. That hundreds of the small- and medium-sized holes of this sort are found in the hard rock of stream beds, usually in or just below existing or recent rapids; that the actual development of small ones in water channels is a matter of historical record and that the swirling water is still deepening others would seem to establish the theory beyond any reasonable doubt. The difficulty encountered in applying this hypothesis, however, to those whose relations to present or ancient stream channels was not demonstrable and the fact that such holes were usually found where the results of glaciation were evident early led to the idea that they were the result of the action of glacial mills. According to Brögger and Reusch,[2] Charpentier, as early as 1841, noted the possible relation of the giants' kettles to glacial action.[3] Hogard, in 1858, presented arguments for the causal relationship of glaciers to the wavy channels and marmites found on the slanting walls of valleys and regarded their presence as

[1] G. H. Stone, "The Glacial Gravels of Maine and Their Associated Deposits," *U.S. Geol. Surv. Mon. 34* (1899), p. 324.

[2] W. C. Brögger and H. H. Reusch, "Giants' Kettles at Christiana," *Quar. Jour. Geol. Soc.*, Vol. XXX (1874), pp. 763, 771.

[3] *Essai des glaciers du Rhône* (Lausanne, 1841).

evidence that the region had been glaciated.[1] Von Post, in 1866, developed the same theory from a study of glaciated regions in Sweden.[2]

The moulin hypothesis for the origin of those eddy holes which are not easily associated with stream action was generally adopted by later writers. Upham, whose writings on the subject are well known, was a strong advocate of the moulin hypothesis which he describes in the following words:

> For the largest and deepest of the giants' kettles, however, to be here noted as discovered in many localities of glaciated countries, I can not doubt that the pothole was cut down exactly at the foot of a great and very deep moulin by its powerful descending torrent. . . . . During the process of slow accumulation of the ice-sheet, the summer melting upon its névé surface would produce multitudes of rills, rivulets and brooks which might unite into a larger stream; and this, pouring through a crevasse and melting out a cylindric moulin, might fall perhaps 100 or 200 feet or more on a moderately hilly region, but probably sometimes 500 feet or more on a mountainous district, while yet the ice motion, though sufficient to permit the formation of the crevasse, might not have gained a definite current to carry the crevasse, moulin and waterfall away from the spot where they were first formed. We may thus explain the continuation of a glacial waterfall in one place while it was excavating one of these giants' kettles. . . . .[3]

Gilbert, in 1905, described potholes due to moulins and considers that successive moulins deepen the same depression.[4] Elston, in 1917, stated the moulin theory as follows:

> After a time the crevasse generally becomes sealed by regelation except where the falling water maintains an opening. Thus a vertical fall develops and the stream strikes the rock bed beneath with great force. Boulders and sand are carried from the surface stream to the well and at the base of the ice the plunging water picks up rock fragments and sand from the ground moraine and the material is used as tools with which to attack the rockbed. With long enough continuance of such action a hole is formed which deepens and assumes the character of a normal pothole of very large size.[5]

[1] H. Hogard, *Recherches sur des glaciers et sur les formations erratiques des Alps et de la Suisse* (Epinal, 1858).

[2] "Bidrag til Jättegrytornas Kännedom," *Oefvers. af Kgl. Vetensk.-Akademiens Förhandl.* (1866).

[3] *Op. cit.*, pp. 28, 41–42.

[4] S. K. Gilbert, "Moulin Work under Glaciers," *Bull. Geol. Soc. Amer.*, Vol. XVII (1905), p. 317.

[5] *Op. cit.*, p. 558.

Svenonius, in 1918, explained the origin of potholes through moulins, considering streams of minor importance. He even assumed that the same moulin may have formed two potholes arranged in steplike succession down the face of a slope, and suggested two ways in which it might have been accomplished. It may be thought that one and the same moulin operated in the two places, closed during a period of cold, possibly a winter, during which the ice moved a few meters. The glacial striae are noted as having a direction in accordance with this suggestion. It may also be thought, according to this writer, that one and the same moulin eroded both holes, using different "grinders" at the same time, or successively, the tools from the upper one spilling over into the lower one and there continuing operations.[1]

Fuller, in 1925, even interpreted glacial features through the number and position of the potholes of the Front Range, Colorado. This writer says:

> The amazing number of potholes, together with their positions on the summits of knobs and bosses of granite and schists, points to unusual features of glacial drainage. It is believed that the potholes mark the sites where extensive crevasses opened from the top to the bottom of the ice where it was strained across the irregularities of its bed during the later stages of the glacial occupation. It appears that the ice was practically stagnant . . . . torrents . . . . plunged over the walls of the numerous crevasses to the rock surface below where they developed glacial mills and deeply grooved channels. . . . .[2]

OBJECTIONS TO MOULIN HYPOTHESIS

Although no one brought forth any direct evidence that moulins produced eddy holes, the hypothesis had this to commend it: it provided the great power apparently needed and could be thought of as providing that power in those places where the location of the holes appeared to exclude the ordinary streams as the agents.

The main objection to the hypothesis lies in the difficulty of conceiving the moulin as existing long enough in the necessary definite form at the same spot, or as reforming in the same manner and at the same spot often enough to account for the work accomplished.

[1] F. Svenonius, "Några Bidrag till Jättegrytornas Morfologi och Förekomstsätt," *Geologiska Förëningens*, Vol. XL (1918), p. 731.

[2] M. B. Fuller, "The Bearing of Some Remarkable Potholes on the Early Pleistocene Glaciation of the Front Range, Colorado," *Jour. Geol.*, Vol. XXXIII (1925), p. 233.

Where the ice passed over knobs or ridges, crevasses may be supposed to have formed repeatedly, but to assume that in each succeeding crevasse the moulin formed over the same identical spot and in the same manner so as to continue the work of its predecessors rather strains the theory of probability. There are no apparent reasons for its so forming.

The assumption that the glaciers in the waning period were stagnant enough to remain virtually stationary for the time required to bore such holes in the hardest rocks, often on steep slopes, presents equal difficulty. Moulins occur near the lower margins of glaciers where ablation is pronounced. If the ice is stagnant the water supply for the mill depends upon that limited portion of the mass that lies directly above it, and which, by its melting, feeds it. All the mills must be kept going and all the holes must be bored by that water (much of which cannot be effective) which comes from the melting of this stagnant block of ice.

In connection with this objection to the moulin hypothesis one may pertinently ask if, where the motion of the ice is so slow as to approach zero, crevasses are likely to form? The commonly accepted idea is that crevasses are the results of strains set up in the ice where and when it moves around or over obstructions too rapidly to permit adjustment without fracture. Stagnancy and melting are not physically compatible with crevassing. Where crevassing does not occur we can hardly postulate moulins. The great holes in the basalt at Taylor's Falls, Minnesota, are near the bottom of a deep valley and are crowded into a very small area. If these were formed under glacial mills when the ice was stagnant, we have the added difficulty of explaining the formation of the crevasse necessary for the moulins over a great depression and the production of a battery of several great mills separated by only a few feet.

Further evidence that these holes are not due to glaciers is to be found in the strong arguments presented by Chamberlin that the Dalles of the St. Croix are the result of postglacial erosion.[1]

The use of the moulin hypothesis to explain the potholes found high above present stream levels is not necessary and in some instances cannot be applied. Many such holes are associated with cols

[1] R. T. Chamberlin, "The Glacial Features of the St. Croix Dalles Region," *ibid.*, Vol. XIII (1905), pp. 255–56.

through which mighty streams may have flowed from temporary glacial lakes. Such lakes were often bounded by rock ridges on the southern side and where the waters overflowed the ridge rapids would form and the conditions for the erosion of eddy holes would exist.

Again streams formed by surface melting and flowing along the margin of a glacier may easily account for the holes found high on the side slopes of valleys. For such potholes as those on the high quartzite bluff east of Devil's Lake, Wisconsin, it must be assumed either that this bluff was glaciated—which it evidently was not—or that some ancient river flowing hundreds of feet above the present lake level across the then-buried quartzite ridge eroded the holes in rapids coursing down its southern slope. The great potholes at Christiana (Oslo), Norway, are cut in rock which was several hundred feet below sea level during the latter part of the glacial period. Unless it is assumed that they were formed during the earlier ice ages and not destroyed by the powerful erosive action of the later flows, one must suppose either that the moulins bored them out far below sea level or that some stream flowed over those rocks. Certainly the moulin explanation is as hard on scientific imagination in this case as the stream suggestion. Brögger and Reusch, who accepted the moulin hypothesis, after a lengthy statement of the difficulties involved in attempting to apply it to the eddy holes mentioned above, aptly said, "Fancy has free room here; but a more cautious consideration may raise the inquiry whether we dare to assert, without further knowledge, that such an extraordinary state of things really did exist, even in the ice period."[1]

EXPERIMENTAL WORK

The obvious difficulties connected with the glacial-mill hypothesis and the lack of accurate data on the mechanics of pothole action led the writer to undertake a series of experiments. It was hoped that the results of such an investigation would throw light on the subject and possibly furnish a better explanation of the peculiarities of form and determine more exactly the conditions essential to the formation of these interesting features of erosion.

[1] *Op. cit.*, p. 770.

In order to carry out these experiments the apparatus shown in plan in Figure 1 and in section in Figure 2 was set up. This consisted of a reinforced concrete tank with long gas-pipe legs (*L*), and was provided with two openings in the bottom. Into the larger of these a glass cylinder (*P*) 8 inches in diameter and 36 inches long was sealed. Into the smaller opening a waste pipe (*W*) was sealed. Fastened to an upright rod (*R*), which was secured in the concrete, was a pipe (*T*) with a somewhat constricted nozzle (*O*), connected with the water supply.

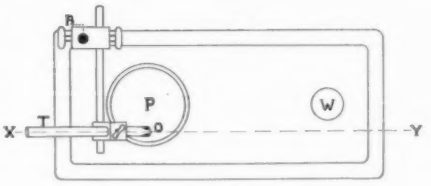


FIG. 1.—Plan of apparatus

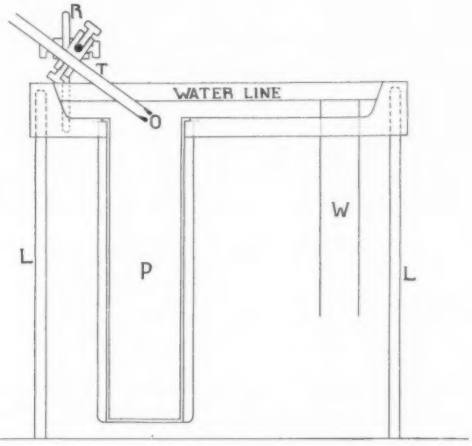


FIG. 2.—Vertical section of apparatus (taken at *X*–*Y* on Fig. 1).

RELATION OF ENERGY TO POSITION OF JET

The following experiments were made to determine the relation of the energy of rotation of the "tools" at the bottom of the cylinder to the angle and location at which the jet strikes the top of the column. The relative energy transmitted to the tools was determined

by noting the number of revolutions which a marker among them made per minute. The tools were represented by a small amount of sand and some marbles. A red ball about three-quarters of an inch in diameter whose density was just slightly greater than that of the water was also placed in the cylinder. This ball, being easily carried by the moving water, acted as a visible indicator of the currents set up in the column of water.

The jet was first placed at an angle of 35° from the horizontal and at the maximum distance, $3\frac{1}{2}$ inches, from the center of the opening, and the number of revolutions of the marker per minute noted. Similar observations were made with the jet at different distances.

TABLE I

Distance of Jet from Center	Jet at 35°	Jet at 55°
	R.P.M. of Marker	R.P.M. of Marker
$3\frac{1}{2}$	33	31
$2\frac{1}{2}$	27	27
$1\frac{1}{2}$	18	20
$\frac{1}{2}$	0	0

A second series of observations was made with the jet at an angle of 55° from the horizontal. The results of these observations appear in Table I.

RELATION OF ENERGY TO ANGLE OF JET

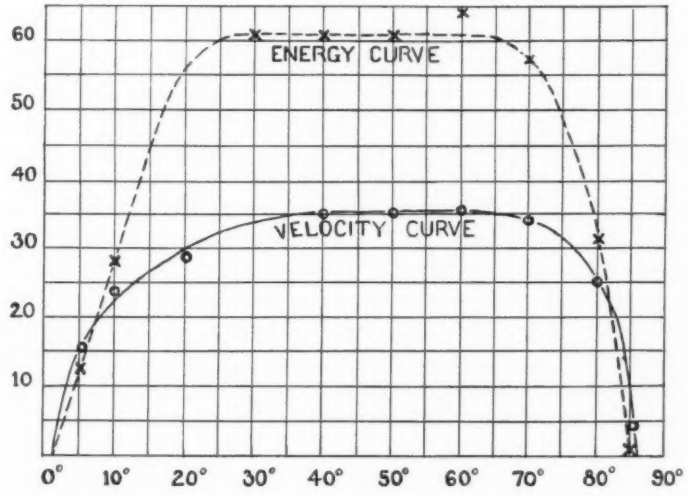
When the jet, placed at the point of maximum efficiency as determined from Table I, was set at 90° (measured from the horizontal), the regular whirling of the sand and ball at the bottom ceased, although occasional vortices appeared. The loose sand and marbles gathered largely on the side of the bottom opposite to the side of the top at which the jet was placed. The finest sand was carried upward and discharged with the water over the rim. The ball would lie or roll erratically around on the bottom at times, and again it would rise with some ascending current. In the latter case it would float about in the upper two-thirds of the cylinder as it was carried by various currents until caught in the strong descending current which would occasionally return it to the bottom. When the jet was set at any angle less than 90° with the horizontal, a vortex was im-

mediately set up in the cylinder. This was clearly indicated by the whirling motion imparted to the tools and the ball. The kinetic en-

TABLE II

Angle of the Jet	Revolutions per Minute	Relative Energy of Rotation
0	0	0
5	16	256
10	23.5	552
20	28	784
30	35	1,225
40	35	1,225
50	35	1,225
60	36	1,296
70	34	1,156
80	25	625
85	4	16
90	0	0

GRAPH FOR TABLE II



ergy of a rotating mass is expressed by the formula $KE = \frac{1}{2}\omega^2 I^2$. The moment of inertia being constant, we can write $KE \backsim \omega^2$. As ω varies directly as N, the number of revolutions per minute, we can write for the energy of rotation at the bottom of the tube $KE \backsim N^2$. Table II

shows in the second column the number of revolutions per minute of the tools at the lower end of the vortex, corresponding to the angle at which the jet was set. In the third column is shown the relative energy of rotation of the tools corresponding to the angle of the jet.

The graph made from Table II shows clearly that with the same energy supplied at the top the angle of impact can be varied through wide limits without much change in the amount of vortex energy transferred to the bottom of the tube. This is probably to be explained by the fact that the decrease in the effective tangential component of the force of the jet as the angle is increased, except for very large or very small angles, is compensated for by the steeper thrust which applies the power farther down the tube, thus decreasing friction losses. It is to be noted, however, that the vortex energy falls off very rapidly when the angle of the jet is brought to within a few degrees of the vertical.

DECREASE OF ENERGY WITH DEPTH

In order to determine the rate at which vortex energy decreased with depth, a smooth false bottom was made to fit the inside of the cylinder as snugly as possible. This was fastened at the center to the lower end of a small rod by means of which it could be placed at any given depth in the tube. A clamp was fastened to a bar extending over the top of the cylinder by means of which the rod carrying the false bottom could be secured in position. A small colored marble was placed on this false bottom, which was fixed successively at the depths indicated in column 1, Table III, the minimum depth used being equal to the diameter of the tube. The jet was set at an angle of 20° with the vertical and placed so as to strike the top of the water column at a maximum radius. The number of revolutions per minute made by the marble as it was rolled around on the bottom by the vortex was carefully observed, and these numbers are entered in the second column opposite the corresponding depths. As the energy varies with the square of the velocity of a moving mass, the numbers in the third column, which are the squares of the corresponding numbers of revolutions per minute, represent relative energy values for the different depths. In the graph accompanying Table III the depths are plotted as abscissas and the revolutions per minute as ordinates for the velocity-curve, and the depths as abscissas and the

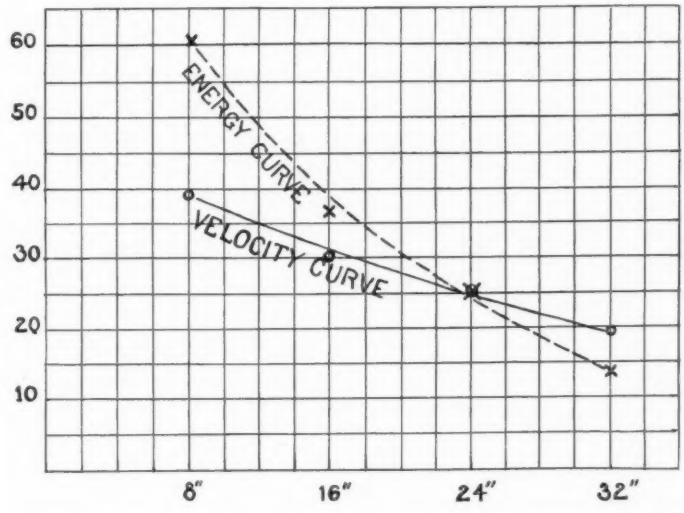
corresponding relative energies as ordinates for the energy-variation curve.

The lower curve shows that the energy available for bottom erosion at first falls off rapidly with increasing depth. At a depth equal

TABLE III

Depth	R.P.M.	Relative Energy
8	78	6,084
16	61	3,721
24	50	2,500
32	37	1,369

GRAPH FOR TABLE III



to four diameters the energy of motion of the tool was less than one-fourth of what it was at a depth of one diameter. On the other hand, it is to be noted that the rate at which the energy of the vortex decreases with depth is a decreasing rate. It is also to be borne in mind that in the natural eddy hole the rate of decrease in vortex energy would be considerably greater, owing to friction losses caused by the irregularity of the rock wall.

CURRENTS IN EDDY HOLES

While experimenting with smaller tubes and a "so-called" grinder, it was noted that the ball would travel in circles or loops that only touched the outside wall at one point. Two things appeared evident: first, there was some centripetal force acting; and, second, the center of the vortex at the bottom of the tube was eccentric.

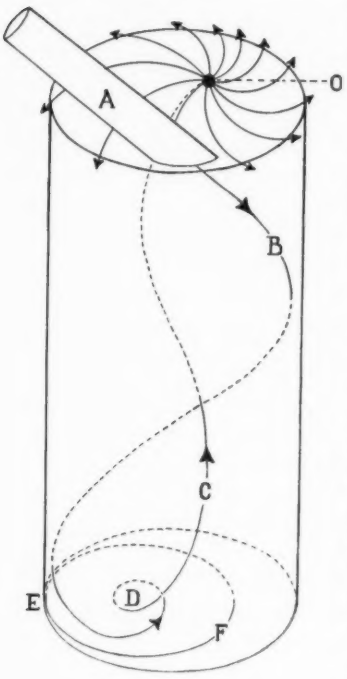


FIG. 3

In the larger cylinder used for the final experiments, when fine sand was introduced it was seen to whirl about an eccentric point as a center and to come in contact with the wall of the tube, if at all, only on one side. Colored marbles introduced traveled in wider circles or loops, *F*, Figure 3, having only the same point of contact *E*, with the wall as the sand. When the jet was quickly shut off the water column would continue to rotate for some time, and the sand which had been whirling about this eccentric point would begin to move toward the center, forming a sharp, cone-shaped heap. Lighter particles traveled around the cone in ascending spirals and often seemed to be lifted by an upward current from the apex of the heap. When crystals of potassium permanganate were dropped in just after the jet was cut off, they were moved into the center with the sand and colored streams from them could be seen rising from the top of the cone, as illustrated at *B* in Figure 4, the diffusion of the rising color forming a distinguishable colored axis in the tube and showing that an upward current existed at the center. When a crystal of the potassium permanganate was placed next to the wall on

the bottom of the tube, as at *C*, Figure 5, and the vortex slowed down, a stream of color, *E*, from the crystal was seen to curve inward toward and even flow up the side of the sand cone, *S*, at the center. Balls only slightly heavier than water seemed to follow the paths indicated by the color and could be seen at times to climb the slope of the sand cone in a spiral manner and repeatedly rise from the apex short distances as though lifted by some upward force.

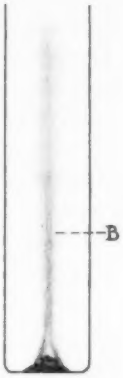


FIG. 4

These facts clearly show that the spirally descending current along the walls of the cylinder, owing to the tangential downward action of the jet, upon reaching the bottom moves spirally in toward the center where it rises along the axis of the vortex. Any solid material escaping from the lower end of the tube must be fine enough to be carried upward by this current. In the 8-inch glass cylinder used for the observations of these currents, with a vortex velocity as high as 80–100 revolutions per minute, very fine sand was lifted only a few inches from the bottom. It would thus seem that in eddy holes, after depth exceeds diameter to any extent, only matter of exceeding fineness would be removed.

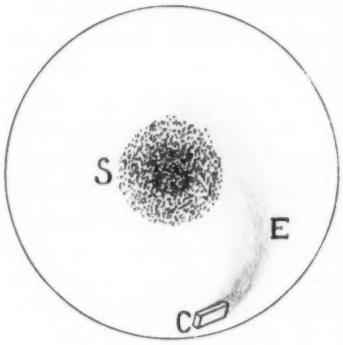


FIG. 5

Some of the fine sand used was dropped into the top of the cylinder and observation made of the velocity with which the larger and the smaller grains sank in still water. These velocities were 0.2 and 0.1 feet per second, respectively. Apparently upward currents of even this low magnitude did not exist with vortex velocities as high as 80–100 revolutions per minute. This in turn would indicate that such holes can be formed only by water that carries a minimum of sediment, except of a very fine form, for if coarse sediment is brought into the

hole faster than it can be reduced to such fineness as makes removal possible, deepening would cease. After an eddy hole has attained a depth in excess of diameter and where the angle of impact is only a few degrees from horizontal, as is probably the case where many eddy holes are forming, only a small amount of new water is driven to the bottom of the hole per minute and so only a small amount has to rise toward the top. The jet plays upon and glances off the top of the water column in the cylinder. Thus most of the water furnishing the energy of rotation never reaches the depths of the tube. This was shown experimentally by coloring the water in the cylinder before turning on the jet. The colored water was rapidly swept out of the top of the tube, but that in the bottom disappeared very slowly.

SPIRAL FLUTING

A striking and fairly common feature of eddy holes of any considerable depth is a sort of spiral fluting. Brögger and Reusch in describing the giants' kettles at Christiana say, "Many show spiral formations, in the larger most perceptible at the bottom; in one case [No. 7 at Kongshavn] the spiral is so developed that the kettle may be compared to the impression of a gigantic snail; in one case of the great Bakhelagel Kettle the spiral formation was so evident that all spectators used some such comparison."[1] This feature is also prominent in several of the remarkable eddy holes in the Interstate Park at Taylor's Falls, Minnesota, and at several other localities. Seeking to explain this feature, Brögger and Reusch experimented with a jet of water and a glass vessel containing some sand and small stones. By making the jet strong enough so that "it worked entirely down, the stones at the bottom were set in motion, and the water driven out took the rubbish with it in a spiral motion upward. The finer rubbish was cast out; the coarser, grasped by the descending stream, was thrown against the bottom, and again taken up in a spiral and so on."[2] Considering the depth and diameter of the St. Croix eddy holes, it would appear impossible for even the descending waters of a deep moulin to furnish the powerful, constant, and definitely directed jet that would operate in the manner described. This would be particularly true of the very narrow and long extensions forming the bottoms in some cases.

[1] *Ibid.*, p. 761. [2] *Ibid.*, p. 765.

No details were given by the foregoing investigators regarding the experiment cited. All attempts of the writer to produce the upward spiral action mentioned by them utterly failed. In shallow vessels the oblique upward motion of the larger particles may have appeared to be spiral due to refraction and the difficulty of observing through the overflow. In all cases when the column of water in the apparatus herein described is caused to rotate by a jet acting at the top, there is a spirally descending current, *B*, Figure 3, along the outer walls. The conditions under which the jet must act to cause rotation of the column necessarily produces such a current and particles thrown in at the top can be seen descending spirally along the outer wall demonstrating its existence. The only current upward under vortex conditions is at or near the cylindrical axis.

SPIRAL VORTEX

In order to explain the spiral fluting the writer was led to consider the mechanics of a cylindrical water column when caused to rotate about a vertical axis by the oblique peripheral impact of a jet of water. The forces acting at the top of such a fluid column would cause the axis of rotation to be eccentric. The rotation of the column of water would displace this eccentric axis in the direction of rotation in proportion to depth and angular velocity. This would make the axis of rotation assume the form of a spiral (*C*, Fig. 3) about the cylindrical axis and the point of application of the vortex energy for erosion at the bottom would be eccentric. In order to test this theory the following experiment was performed.

The false bottom previously used to vary the depths of the glass cylinder was placed at the bottom of the cylinder with a small amount of sand on it and the jet opened. When the column had reached its maximum rate of rotation, as shown by the activity of the sand as it whirled about an eccentric point at the bottom, the false bottom was slowly raised by means of the attached rod. As the length of the cylinder was thus gradually lessened, the whirling pile of sand slowly changed its position, moving once around the center for a decrease in depth of the tube of about three diameters. As the depth was again increased, the whirling sand heap traveled in the opposite direction about the center. It was often noted when the water was first turned on in these experiments that a spiral line of

fine bubbles appeared, evidently marking the real axis of rotation of the water column where dissolved air was freed by the decrease in pressure due to centrifugal force.

These results appear to demonstrate the spiral form of the vortex axis in the water column. The working end of this axis is obliquely directed and off center at the bottom of the tube, and this off-center position moves about the axis of the hole as it is deepened. The spiral vortex thus acts as a sort of spiral tool and under favorable and constant conditions drills into the rock in "corkscrew" fashion, thus giving rise to spiral fluting.

The position of the upper end of the spiral axis, *O* in Figure 3, varies somewhat with the location, *A*, of the driving jet, with the angle it makes with the surface and with the energy of the jet. The number of turns in this spiral axis for a given depth, and therefore the position of the lower end of the vortex axis, *D*, on the bottom of the tube, would be determined by these same factors and in addition by the angular velocity of the water in the tube—a factor which in turn varies with depth. In the 8×36-inch tube used, when the jet was moved from the maximum distance from the center to a position as near as possible to the center and still maintain the vortex, the lower end of the vortex backed up on the bottom with respect to the direction in which the water was rotating, about 120°. When stream conditions cause such angular oscillation of the working end of the vortex, the spiral nature of the drilling action will not be evidenced in the form of the hole. It should be noted that the working end of the vortex is not perpendicular and therefore that the vortex tends to move the tools in circles whose planes are not horizontal. The drilling action of the vortex at the bottom of the hole on that account is directed outward at some angle from the vertical. In short experimental tubes this outward deflection from the vertical was sometimes observed to be as much as 30°–40°. If the conditions are such as to cause the working end of the vortex to continue in one spot too long, the result will be a hole of reduced diameter leading off from the bottom of the main hole at some angle from the vertical. The strongly deflected and reduced extension at the bottom of the 60-foot eddy hole at Taylor's Falls was probably produced in this way.

GRINDING STONES

The finding of rounded stones in eddy holes led to the conclusion that they were important agents in the boring of the holes. The ease with which the revolution of round stones in the bottoms of a jar of water could be demonstrated by properly directing a jet of water into the jar practically confirmed the idea. These rounded stones have been termed "grinders." For obvious reasons only a few of the very deep eddy holes have been cleared of the material that has accumulated in them. Authentic records or logs of these excavations were seldom made. Of those made and published some of the most definite and trustworthy are the logs of some of the giants' kettles at Christiana by Brögger and Reusch. This work was apparently done under the direction of Professor Kjerulf. The writers distinguish two types of grinding stones: one type "perfect or regularly elliptical in form" and a second type "less perfect in the elliptical tendency in one or another of the three transverse sections."[1]

The contents of a hole 4 feet in diameter and 12 feet deep are described for the first 8 feet as consisting of rubbish from road-building and ordinary moraine matter including a couple of regular stones of the second type. The last 4 feet the authors describe as follows: "Under these came less perfect grinding-stones, in all sixty, mingled here and there with a single one of the perfect grinding-stones, the number of which increased toward the bottom, where they predominated; there were in all forty. The finer rubbish at the bottom was also angular and irregular; and now and then fine sand appeared at the sides of the kettle." Speaking of another hole 34 feet deep and 8 feet in diameter, the same authors state: "At thirty feet there were two grinding-stones, and all the stones began to be more rounded. About six perfect ones were found at the bottom. The largest stood vertically near the deepest point of the kettle; its dimensions were 22, 17 and 15 inches and it weighed three cwt."[2] The word "perfect" as applied to grinding-stones in the foregoing quotation should be interpreted in the light of the dimensions given in the last sentence. The same writers a little farther on say: "The grinding-stones we found were never less than three inches; they were seldom very perfect when over one foot long."[3]

[1] *Ibid.*, p. 758. [2] *Ibid.* [3] *Ibid.*, p. 761.

If the more or less rounded stones in the preceding descriptions are the tools with which the last work of deepening was accomplished, two difficulties present themselves. First, the number of tools described and their size would seem to make packing inevitable and thus the deepening would be stopped. Second, they are more or less completely separated by clay and small fragments packed in after the manner of glacial drift. If these rocks are the last grinders left in the hole as the action slowed down, this "driftlike" packing is anomalous. The statement by Brögger and Reusch that "the finer rubbish at the bottom was also angular and irregular"[1] is illuminating. How did this fine and angular material get under the last grinder?

The large eddy holes at Interstate Park, Taylor's Falls, Minnesota, are situated on a steep, irregular slope in an old channel of the St. Croix River. This old channel bed forms the west bank of the present channel and ranges from about 20 to 70 feet above the present river level. At the foot of the major portion of the slope is a deep, irregular pool filled with muck and forming a level swamp about 100 feet wide and 125 feet long. The water cascading and swirling down the slope formed the eddies which operated the tools that eroded the holes and then at the foot gouged out the hole occupied by the swamp. A deep hole of this group was cleaned out during the summer of 1927. The following is taken from a letter received from the Interstate Park Commissioner, Dr. C. M. Truesdell, on the contents of this remarkably deep hole, the lower part of which is only 3 feet in diameter and deflected strongly to the southwest. "The most symmetrical one was filled to within 8 feet of the surface. We found six feet of water, then 4 feet of moist muck, from that on for 26 feet the deposit resembled decayed vegetation, with very few rocks, and from that depth on the gravel became free of any muck or soil. At the base we found no rock to exceed forty pounds in weight." Small stones of marked roundness appeared throughout the whole 24 feet of gravel that filled the bottom of the hole and therefore the rounding process must have preceded their entry into the hole. One remarkably round stone (Fig. 6) was taken from one of the other large holes. The white ruler shown is 6 inches long. This rock was found near

[1] *Ibid.*, p. 758.

but not in actual contact with the bottom and possibly served as a grinder in the hole in which it was found.

The filling of the 60-foot hole tells the story of decreasing stream energy when the river began to shift to its newer channel. Early in this change the erosion at the bottom of such a deep hole would cease and the hole would begin to fill with bed wash. While the channel current was still strong it would contribute some large stones rounded by stream rolling and as the current became weaker the larger stones

FIG. 6.—Grinder (?) from St. Croix River pothole

would become fewer. After the channel was abandoned by the river, wind and rain wash would continue to fill the hole with leaves and fine sediment and produce muck. The shallower holes would continue active longer and therefore have a much shorter period during which the stream would be able to contribute its bed wash in the form of stones and gravel. As the conditions at the different eddy holes in this irregular channel would vary greatly during the waning period of the river and as rejuvenation of current might occur at times, the filling of the different eddy holes would, of course, vary greatly.

That a quite perfectly rounded stone of appropriate size found in contact with the bottom of a hole may be a grinder can hardly be doubted, but that those separated to any degree from the bottom by

finer material can be so regarded seems open to serious question. That many of these rocks are found to be somewhat more rounded than the average of moraine boulders may not indicate so much that they are grinders as it does that the eddy hole was formed by and in a stream rapid, which, after drilling the hole, under different conditions contributed some of its well-rounded waterworn boulders to the filling. While the hole is shallow and energy is abundant, grinders may be important factors, but in holes where the depth is relatively great they would be a hindrance. It was found that when half-a-dozen small marbles ($\frac{1}{2}$–$\frac{3}{4}$ in.) were placed in the bottom of the 8×36-inch cylinder, they would frequently pack while the sand remained actively at work. When concrete bails of the same size, but flattened 25 per cent, were substituted for the round and smooth marbles, they remained stationary. The water jet used supplied energy at the top of the tube at approximately 1/10 horse-power. While steep rapids or a fall might make much more power available, it is doubtful if the amount efficiently directed into an 8-inch hole would greatly exceed that used in the experiment.

The size of the rocks that a stream is able to move along its bed is determined by several factors and varies as some power of the velocity between the second and the sixth according to conditions. In the stream bed the current has the help of the gravity component, which on the slopes of rapids would be very great and might easily bring to an eddy hole rocks which the velocity of the vortex at the bottom, unaided by any gravity component, would be unable to move. It would appear, therefore, that in order for the vortex to use as grinders rocks contributed by the stream, the vortex velocity at the bottom of the hole must exceed considerably the stream velocity. This might be possible where the water driving the vortex is directed down a steep chute and enters the top of a hole that is not too deep and under the most efficient conditions, but to regard it as probable for each of the many large eddy holes, closely grouped, as at the Interstate Park and many other places, certainly requires strong imagination. The larger rocks that a stream would be able to move the vortex of an eddy hole ordinarily would be unable to use, and its action would be hindered or stopped by their introduction. This suggests strongly the use of small tools, probably sand and fine gravel, in

the erosion of these holes. In gouge holes and plunge-pool holes the energy at the bottom is relatively greater and larger stones may be used. From theoretical considerations as well as the results of these experiments the writer is led to the conclusion that most of the rocks commonly regarded as grinders are simply waterworn stones washed into the hole after the conditions that gave rise to the vortex that drilled it ceased to exist.

FORCES ACTING ON TOOLS

At the bottom of the tube in which the typical spiral vortex exists there are two opposing forces acting radially on the particles used as tools. Centrifugal force tends to throw them outward from the center of the vortex while the current across the bottom of the tube, previously mentioned, tends to carry them inward. This spiral inflow across the bottom of the hole focuses at the vortex center and by concentration becomes stronger as that point is approached. On the other hand, centrifugal force, which for a given mass varies as V^2/R, increases with distance from the vortex center. With change in the size of the tools the effect of each of the foregoing forces would change. The force on a particle due to the centripetal inflow would vary as the circular area, that is, as the square of the radius, while the centrifugal force which is a function of the mass would vary as the cube of the radius. A gravity component varying with the slope in round-bottom tubes must also be considered as well as difference in density and form. And, finally, the relative values of these different factors appear to vary with the angular velocity of the vortex and its eccentricity. A theoretical formula expressing the radius of action of a particle in terms of the preceding factors appears practically impossible.

As the angular velocity was decreased in the flat-bottom experimental tube, the balls and particles of all sizes traveled in smaller circuits, and as motion ceased most of them came to rest in a common group at the center of the bottom of the tube, to which point the lower end of the vortex always shifts when the driving jet is closed. This showed that the centripetal force exerted by the spiral inflow at the bottom prevailed over centrifugal force for all sizes of tools when the angular velocity became small. This effect is accentu-

ated in round-bottom tubes where the gravity component becomes an added centripetal force. On the other hand, no matter how much the angular velocity was increased, the smaller tools remained at the vortex center.

In order to determine the different relative effect of these forces on tools of different size, glass beads ranging from 8/100 to 40/100 of an inch in diameter were placed in a round-bottom tube 7 inches in diameter and 14 inches long. With an angular velocity of about 60 R.P.M. at the bottom of the tube, all the beads remained most of the time close to the vortex center. When the velocity was made 120 R.P.M., the balls above 20/100 inch soon escaped the action of the spiral inflow, forming a group which persistently swung in wide circles. The balls below 14/100 inch formed a group which remained persistently near the vortex center and the intermediate size shifted intermittently from one to the other of these two groups. This suggests that the size of the tools is a factor in determining the diameter of eddy holes.

To determine the effect of different densities, steel, ivory, and glass balls of the same size were used. The denser balls, once having escaped the action of the spiral inflow at the vortex center, traveled persistently in wide circles and seldom returned to the center. The less dense balls less often escaped from the center and were usually soon forced back. This is to be explained by the fact that while increase in density increases the centrifugal force, and the gravity component due to the round bottom, it does not affect the force exerted by the spiral inflow. This would suggest that the density of the rocks used as tools may also be a factor in determining diameter.

FORM OF EDDY HOLES

The form of an eddy hole depends upon energy supply, tools, and rock structure. The spiral fluting has already been explained by the spiral vortex previously demonstrated. Irregularities in the walls of the hole may be caused either by varying hardness of the rock or by variation in structure which determine its resistance to erosion. They may also be caused by variations in power supply which affect the rate of erosion and eccentricity of the working end of the vortex. And finally they may be caused by variation in the kind of tools supplied.

For example, if a vortex is drilling by the use of sand as tools and the stream contributes a sufficiently rounded rock to act as a grinder, this rock, swinging around the vortex center in a wider circle, will pound the point of the wall nearest to the vortex and thus form an irregular depression in the wall.

The relation of depth to diameter is determined to some extent by rock structure. In stratified rocks we may in general expect to find the ratio of diameter to depth greater than in massive rocks. This is due to the fact that in widening the hole in stratified rock the tools are usually attacking the lamina edgewise, the condition under which they are least resistant, whereas, in deepening the hole they are usually working on the surface of the lamina, the condition under which they are most resistant. The ratio of depth to diameter is mostly determined by those stream conditions which determine how long the proper conditions for boring will continue at the points where eddy holes are started. If favorable conditions for drilling are maintained long enough at a given point, the hole will be deepened until the effective energy at the working end of the vortex decreases to the point where it is no longer able to move the tools. It is doubtful whether this has ever happened. In most instances the work appears to have stopped before great relative depth was attained, either by withdrawal of power supply or by choking with sediment.

The variation in diameter in a given hole may be caused in a few instances by vertical variations in the hardness of the rock. The more usual cause, however, is a change in the diameter or density of the tools or in the power supply. For the same angular velocity larger tools, which revolve in larger circles about the center of the vortex, would, if supplied, cause an increase in diameter. The radial range of the tools varies with the angular velocity and so a change in the amount of energy supplied would affect the diameter in the hole.

The form of the lip or margin of an eddy hole is often an accident of rock structure. The manner in which the water leaves the hole is the important mechanical factor. The entering current is of secondary importance. In Figure 7, let the arrow, B, indicate the direction of stream flow and the cross-section area, A, the region where the current that furnishes the energy for the eddy enters the hole. Where this water enters there must be a downward motion. As the

water is deflected around the inside of the tube, this downward momentum produces a spiral descending current next to the wall. As has been previously shown, this current flows inward at the bottom and rises as a spiral ascending current. At the top of the tube this ascending current moves outward spirally together with a large part of the water input, which, as has been shown, glances upward after impact. This spiral outflow will be modified by three things: first, by the shape of the rock surface adjacent to the hole; second, by the force and direction of the stream flow across the opening; and third, by the input current. The effect of this last factor is to prevent outflow over that part of the rim adjacent to the input area, and the effect of the second, varying in degree with the force of the stream, is to decrease the outflow on the upstream side and to increase it on the downstream side. Where the bedrock surface into which the eddy holes are bored is practically level, the lip or rim should show a depression due to outflow erosion on the downstream side. This opening or depression is not cut through the rim radially, but spirally, and indicates the sense in which the water whirled in the tube. Owing to the modifying influences of the shape of the rock adjacent to the rim (and such influences are generally necessary to start the eddy) and to subsequent erosion, such typical outflow depressions are seldom distinguishable.

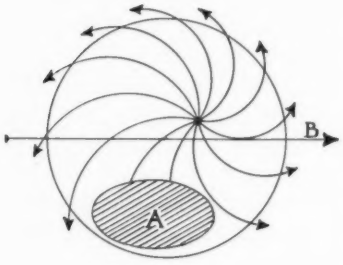


FIG. 7

GOUGE HOLES

Gouge holes may be defined as elongated holes with a more or less flaring U-shaped vertical section parallel to stream flow and caused by the oblique direct impact of water.

The length of the diameter at the top, measured in the direction of stream flow, is often several times the transverse diameter, or width. This longer diameter usually decreases rapidly with depth, giving rise to a longitudinal section of the form shown in Figure 8. The amount of the flare, or angle formed by the sides of the U, depends

upon the angle of the impact of the water. As the direction of the eroding jet approaches the horizontal, the U-shape flares more, becoming a long groove, and as it approaches the vertical the U closes up as shown in Figure 9 and the hole approaches in form the plunge-pool hole. The typical gouge hole is characteristic of steep rapids, and as the water passes into and out of the hole with little or no decrease in velocity, it is able to handle a large supply of tools when available without choking and filling. The great force with which the tools are driven against and up the side of the hole makes each particle very effective. For the most part each particle is used only once, but in the deeper and less flaring gouge holes, when and where the velocity of the entering current is less, a rotary motion of the water at the bottom of the hole about a transverse horizontal axis may carry particles of appropriate size in circles as at *C*, Figure 9, using them repeatedly. The tremendous force with which the water is driven against the lower side of the hole effects erosion directly by producing sufficient pressure in minute openings to separate surface particles from the mass. These openings may be a characteristic of the rock; they may be caused by solution, or they may be the result of the differential expansion and contraction of the constituent minerals, owing to changes in temperature. Freezing, when it occurs, would enlarge the openings and loosen the particles, thus assisting in this effective toolless process of erosion. Some fine typical examples of gouge holes have been eroded in the index granite at Sunset Falls, near Index, Washington.

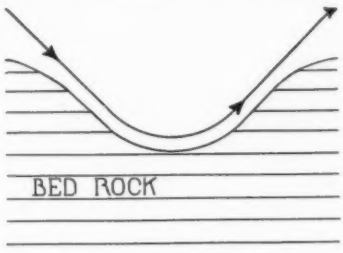


FIG. 8.—Section of gouge hole

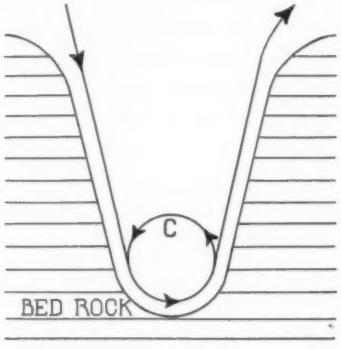


FIG. 9.—Section of gouge hole

PLUNGE-POOL HOLES

The third type of holes produced by river erosion is the plunge-pool hole. These are holes produced by the action of freely falling water. Where the falling column of water is approximately cylindrical and where the recession of the falls is slow, the hole eroded usually has a circular cross-section. If the stream carries only a small amount of coarse bed wash, so that the energy furnished at the bottom of the hole can wear it out in the grinding process as fast as it is contributed by the stream, the hole may attain considerable depth. The plunge-pool hole at Niagara Falls is reported by Spencer to be 72 feet deep.[1] The deepening process will be terminated, as in the case of other potholes, by anything that brings about an insufficiency of energy at the bottom of the hole to wear out or wash out the bed-wash material as fast as the stream introduces it. This condition may result from the decrease of energy at the bottom due to increased depth, or from a decrease in the amount of energy furnished by the stream, or by an increase in the amount of bed wash transported by the stream.

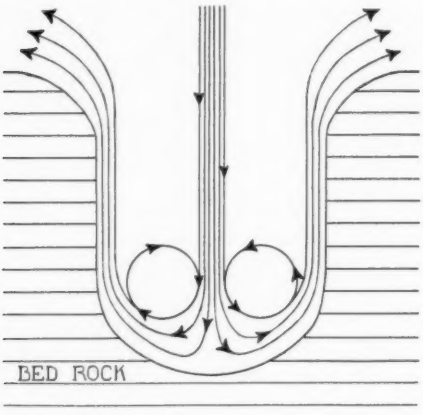


FIG. 10.—Section of plunge pool

The mechanical action in the formation of such holes is similar to that in gouge holes. The water enters the hole vertically and near the center; continues downward along the cylindrical axis to the bottom where it spreads radially toward the sides of the hole, thence rising in a cylindrical shell and overflowing at the top (Fig. 10). The U-shaped path of the water as it is deflected at the bottom sets up a rotation in each vertical radial plane. This causes the water in the

[1] J. W. Spencer, "Sounding in Niagara Gorge and under the Falls," *Sci. Amer.*, Vol. LXXXIX (1908), pp. 76–77.

bottom of the tube to act somewhat like a circular roller continuously rolling downward on the inside, outward on the bottom, upward on the outside, and inward on top. This circular rolling action of the water carries the small tools around in vertical circles as indicated by the arrows in Figure 10, eroding the bottom and sides. It also rolls the larger tools outward and upward on the curved bottom, but when they reach the outer part of the circle where the force acting upon them is less, they stop and roll back downward and inward only to be caught by the stronger outflow and carried outward again. The larger tools thus operate in a sort of oscillating manner. Although the movement of the tools will vary with the many irregularities of the inflow and the shape of the bottom of the hole, their action will be in the main radial and vertical. The evenly distributed action of tools thus operated will usually give rise to evenly eroded bowl-shaped holes except as modified by varying hardness in the rock mass being eroded. When any fluting effect occurs it will be radial or vertical.

If the width of the falling column of water greatly exceeds the other horizontal dimension, the plunge-pool hole will have a greater diameter at right angles to the stream than parallel to it. By recession of the falls the plunge-pool hole is elongated upstream, forming the deeper part of the channel of a gorge, the upper part of which is produced by a caving in process as the plunge-pool undercuts the face of the fall.

RESULTS OF POTHOLE EROSION

The three types of holes mentioned have long been recognized as a most effective *modus operandi* in the channeling of resistant rocks by rivers. The results of this method are especially evident in the narrow canyons of small streams. The irregular forms of Watkins Glen, in New York, and of Coldwater Canyon, a little tributary of the Wisconsin River at the Upper Dalles, just above Kilbourn, Wisconsin, are splendid examples of the pothole method. These streams are still lowering their channels by this method, and the evidence of its effectiveness in the past is found in the remnants of many pothole surfaces in the side walls of the gorges. In Coldwater Canyon part of a large pothole in one of the walls, called the Devil's Jug, indicates

an original size of 35 feet in diameter and about 70 feet in depth.[1] Many of the streams flowing down the steep slopes along the north shore of Lake Superior are cutting their channels downward and backward into the hard rock more or less by pothole erosion (see Fig. 11). The numerous and striking examples that can be cited of this effective method of channeling in rock evidences its importance in the process of corrasion.

FIG. 11.—Pothole in the bank of the Temperance River near the north shore of Lake Superior.

The adhesion of water to rock is greater than the cohesion of water, from which it follows that all rocks are covered with a fixed layer of water. This layer of water not only protects the rock from the effect of the water flowing over it, but also permits many varieties of algae to secure a "foothold." This algal growth which often covers the rocks in rapids still further protects them from wear. For erosion to occur the water itself must strike against the rock surface with sufficient force to break through the fixed layer, or it must dash or roll against the rock surface some solid particle which will break through and produce wear. A stream that does not carry tools therefore does not erode except under falls or in precipitous rapids. Much of the erosion in plunge pools and gouge holes is of the toolless type,

[1] H. E. Cole, *Baraboo, Dells, and Devil's Lake Region* (3d ed., 1924), p. 18.

although tools when present greatly increase the effect. Eddy holes must have some tools but only limited amounts are needed as they are used so efficiently, each one being worn out completely. It follows thus that pothole action is a most important method of erosion in streams which transport very little solid material except in a very fine state.

Potholes are characteristic of those parts of streams where the bedrock is resistant and the flow more or less rapid or precipitous. Such rapid or precipitous flow generally occurs where hard rock, trending across the stream, has decreased the rate of channel deepening and thus produced a temporary baselevel for the action of the waters above, while still permitting deepening of the channel below. As soon as this baseleveled condition obtains above the rapid, the slow-moving stream will bring to the swifter waters only a limited supply of erosive material and most of that in too fine a condition to be very effective. For these reasons pothole action, which can proceed effectively with a minimum of tools, constitutes the most important means in many instances for the removal of such stream barriers. This relation of pothole action in rapids to temporary baselevels is strikingly illustrated by each of the principal groups of potholes at Interstate Park. The group in the park proper is so related to the former level in the soft sandstone above the bridge, while the group just below the dam is related in the same way to the level above the falls, or rather rapids, on the site of which the dam is built. These level stretches acted as settling basins reducing the sediment carried to that small amount which made pothole action the important means of erosion in the rapids.

CONCLUSIONS

There are three definite systems of water circulation possible in stream potholes, depending on the position and angle at which the driving current enters the hole. The tools will be handled in entirely different ways by each circuit.

Spiral circuits.—In the spiral circuit (Fig. 5) the tools are moved in a circular path, approximately in a horizontal plane, and the center of this path is eccentric at the bottom of the hole. The amount

and direction of the eccentricity vary with energy input, jet position, jet angle, and depth.

The eddy hole resulting from this action will be generally cylindrical, except as influenced by varying hardness or structures in the rock formation, but will often vary in diameter and may show spiral fluting.

Ordinarily only very small solid particles are removed from deep eddy holes by the relatively weak ascending current.

Spiral fluting and the reduction in size and deflection from the vertical in the bottom parts of some eddy holes are due to a spiral vortex (see Fig. 3).

The deeper the hole, the smaller the tools that can be used. Large grinders seldom if ever are used in deep eddy holes. Most so-called large grinders are contributed after "grinding " has ceased.

Plane circuits.—In the plane circuit the tools are moved in and out of the hole, or about a horizontal axis in a loop whose plane is vertical (see Figs. 8 and 9). They are driven diametrically across the bottom and against and up one side of the hole.

The cavities resulting from this action are mostly of oval or elliptical form in cross-section. They are usually greatly elongated in the direction of the stream flow. They are never pot or kettle shaped, neither are they in any sense eddy holes. They may properly be called "gouge holes."

Cylindrical circuits.—In the cylindrical circuit, so called because the outflow is in the form of a cylindrical shell, the tools are moved outward radially against and up all sides of the hole. They soon escape from the ascending current, either by elastic rebound from the wall or by deflection, and fall or are driven to the bottom by the descending current. The cycle is continuously repeated.

This action gives rise to the typical plunge pool beneath sheer falls. The cross-section of the cavity may be round or transversely elongated, depending upon the relation of the width to the depth of the stream. By recession of the falls such holes are elongated upstreamward.

General conclusions.—All the preceding circulation circuits are the natural result of well-known physical laws and can be easily demonstrated with apparatus similar to Figure 1.

Change in position or angle of the jet may change one circuit into another and therefore some holes may be expected to show a combination of forms.

Deepening of channels and recession of rapids as well as falls depend largely on pothole action in streams where the quantity of tools is greatly limited and the bedrock is relatively hard.

The causal relation of moulins to eddy holes is doubtful.

THE COAHUILA PIEDMONT, A PHYSIOGRAPHIC PROVINCE IN NORTHEASTERN MEXICO

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ABSTRACT

The Coahuila Piedmont is a physiographic province in Northeastern Mexico, lying between the Rocky Mountains and the Coastal Plain. A discussion of its physiography shows it to have had a physiographic history similar to that of other areas along the Rocky Mountain border. The surface is occupied by Comanchean-Cretaceous strata, and Pliocene (?) Reynosa conglomerate. Two principal structural units are the Sabinas and Huerfana basins. Gently dipping structure and low rolling topography prevail.

INTRODUCTION

This paper discusses the physiography and general characteristics of an area of several thousand square miles in Northeastern Mexico. The greater part of the area lies in the state of Coahuila, although small parts of Nuevo Leon and Tamaulipas are also discussed. The writer, associated with Mr. W. F. Eastman, camped in the area for approximately a year, and the following material was gathered incidental to a geological survey.

FIG. 1.—Index map showing general location of area (shaded). (All illustrations in this article are by the author.)

GENERAL DESCRIPTION

In the northeast of the Mexican state of Coahuila, lying east of the arc of the Rocky Mountains which leave the United States through the Big Bend country of Texas, is an elongate physiographic entity herein called the Coahuila Piedmont. It is a long strip of country, semi-barren and desolate, with low rolling hills, and flat, baked, mesquite-dotted flood plains; glaring limestone-floored ar-

royos, and undulating brush-covered waste land, lying between the flanks of the Rocky Mountain system and the gently gulfward-dipping cuestas of the Coastal Plain. It has not such ultra-distinctive characteristics as, for example, the Rocky Mountains, but is in con-

FIG. 2.—A portion of the Huerfana Hills (see map, Fig. 4)

trast with the Gulf Coastal Plain by a difference of the order of that separating the Colorado Piedmont from the High Plains. In very few instances do elevations above the surroundings exceed 200 or 300 feet, and lesser relief is by far the general rule. Ruggedness is absent, and regularity of contour usually prevails.

FIG. 3.—Typical Eagle Ford shale topography, Huerfana Hills

The summer heat and scarcity of rainfall produce a semi-desert effect which makes permanent settlement of parts of the country an exceedingly precarious undertaking. One can travel 40 miles in the northern section without encountering water. However, the completely desolate portion is relatively small, and the greater part is fit for grazing. The climate is slightly less arid, and the terrain slight-

ly less barren, than in the Basin and Range province of the United States. In summer the thermometer registers well over 100°, while during the northers which sweep the country at intervals through the winter the freezing point is often passed.

GEOLOGY

The formations occupying the area are the Edwards-Georgetown[1] limestone, Buda limestone, and Del Rio clay, of the Comanchean; and the Eagle Ford limestone and marl of the Cretaceous. In the southern part, northwest of Lampasos, Nuevo Leon, are Cretaceous beds of San Felipe limestone, and Taylor and Novarro (Papagallos) shales. In the Huerfana section 40 miles west of Del Rio are a few local basic intrusions, and others are reported to exist in the Peyotes Hills southeast of Allende.

From the east margin of the province, the beds of the Gulf Coastal Plain dip gently gulfward, but there is no persistant regional dip in the Piedmont area. Sectional dips may persist there for 40 or 50 miles, but a constancy of dip such as characterizes the Coastal Plain is lacking. The beds are generally flat, dips of over 6° being rare except along the mountain flanks and in areas of local folding such as the Peyotes Hills, Lomeria la Laja, and other small folds.

The two main geological units in the province are the Sabinas basin, which includes the town of Sabinas, and the Huerfana basin just west of Del Rio, Texas. They are separated by a topographic and structural high along the axis prolonged, of the Burro Mountains, which becomes also the axis of the Peyotes Hills. In these shallow basins, the Upper Cretaceous rocks lie surrounded by Lower Cretaceous or Comanchean strata.

PHYSIOGRAPHY

A great portion of the Coastal Plain in Northeast Mexico is covered by the Reynosa formation of Pliocene or early Pleistocene age.

[1] The term "Edwards-Georgetown" was introduced by W. F. Eastman in a private report (1927), to designate the ± 500 feet of thick-bedded, massive, gray limestone which forms the conspicuous cliff-making caprock in the Burro Mountains. Although two divisions, an upper and lower, were distinguished in the field, the two units were not deemed sufficiently dissimilar stratigraphically to warrant their being separated into two distinct formations. At the same time, it seemed expedient to indicate the Texas correlatives, without further complicating the already confusing nomenclature by introducing new names.

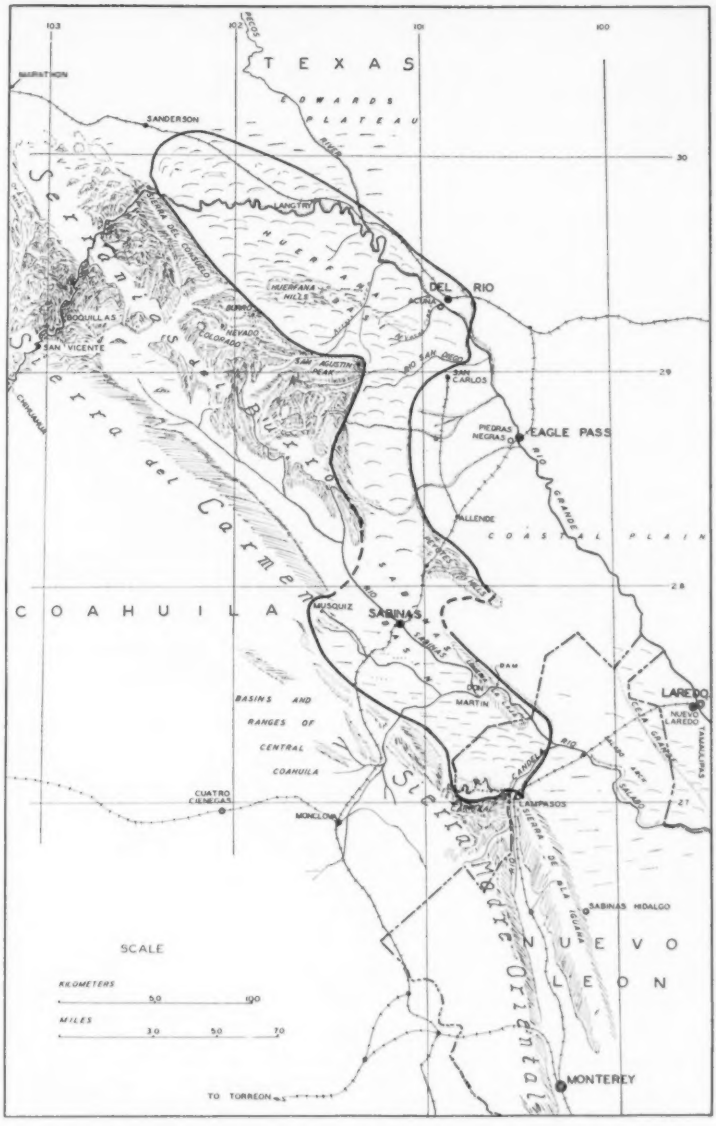

FIG. 4.—Map of northeastern Coahuila and portions of Nuevo Leon, Tamaulipas, and Texas. The heavy line passing just north of Del Rio, along the east front of the Serranias del Burro, and to a point at Lampasos, incloses the Coahuila Piedmont. The mountain ranges west of the Serranias del Burro are not shown. Northwest of Monterey, only the Sierra Madre front is shown in shading, the various units farther west being outside the scope of this paper.

It is a conglomerate blanket varying in thickness from 0 to 70 to 100 feet. The upper surface of the Reynosa, projected across recently dissected arroyos and channels, forms an almost unbroken plain over vast areas. This surface must have originally merged into the mountainous contour along the flanks of the Sierras to the west and southwest; and near Lampasos, Nuevo Leon, this condition actually exists. The Reynosa blanket extends southwestward to the very flanks of the Sierra de la Iguana, and even up arroyos into the Sierra, itself. From Lampasos northwestward, however, the westward edge of the Reynosa surface swings away from the mountains. Lampasos, thus, is the point of a wedge of territory which continues, as an ir-

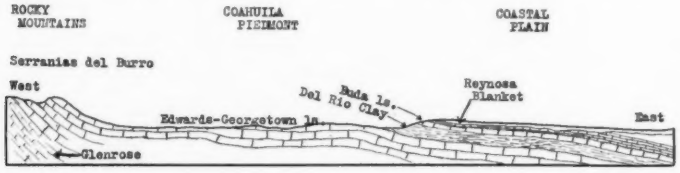

FIG. 5.—Generalized profile across the Coahuila Piedmont from west to east a few miles south of San Carlos. This figure illustrates the position of the rolling topography of the Piedmont, between the Rocky Mountains and the Coastal Plain.

regular strip, to a short distance north of the Rio Grande, and which may be considered as a zone of transition between the mountains and the Coastal Plain. It occupies a position analagous to that of the Colorado Piedmont between the Rocky Mountains and the High Plains. The course of the boundaries is shown on the map (Fig. 4), and need not be enumerated. The eastern border of the Coahuila Piedmont, however, is not always the inner edge of the Reynosa. In some areas the slight increase in dip toward the mountains has brought harder rocks to the surface, and in such areas the region is limited by scarp or cuesta topography. At Del Rio, and for possibly 50 miles to the south, the demarkation between the Coastal Plain and the Coahuila Piedmont is emphasized by the presence of the soft Del Rio clay between the Buda limestone and the Edwards-Georgetown limestone. Along the east edge of the outcrop of this soft formation is a scarp capped by the Buda limestone. The result of the Del Rio formation is to increase the difference in relief in

passing from the Coastal Plain to the Piedmont by an amount governed by the extent of differential erosion between the limestone and Del Rio clay (see Figs. 6 and 7) at any particular point. In the region southward from Del Rio, the border of the Piedmont roughly coincides with the Comanchean-Cretaceous contact.

Westward from Del Rio, near the northerly edge of the Huerfana basin, still different conditions prevail. In this section, the Rio Grande flows near the center of an ovaloid structural basin occupied by the Eagle Ford formation. Most of this Eagle Ford area, which makes a typical topography of abundant rounded, elongate, and

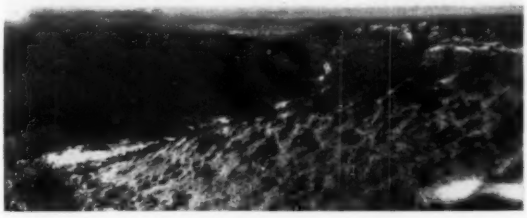

FIG. 6.—The border of the Coahuila Piedmont a few miles south of the San Diego River. To the right from the top of the scarp is the Coastal Plain. To the left is the rolling country of the Piedmont. The caprock is Buda limestone overlying the Del Rio Clay.

conical hills, lies in Coahuila. But, on the American side, a small area, also characterized by the same type of topography, extends into Texas to points near the main line of the Southern Pacific a few miles north of Del Rio, Comstock, and Langtry, and a few miles south of Sanderson. This small area along the border on the American side is closely related structurally, physiographically, and in appearance to the adjacent part of Coahuila. Hence, it is suggested that it be included in the Coahuila Piedmont instead of the Pecos Valley or Edwards Plateau provinces. The boundary might be drawn where the Rio Grande-ward dips into the Huerfana basin interrupt the continuity of the Edwards Plateau. The younger beds thus brought down, and the change in dip, give rise to a type of topography different from that produced by the Edwards-Georgetown limestone in the Edwards Plateau; and the irregular hilly relief

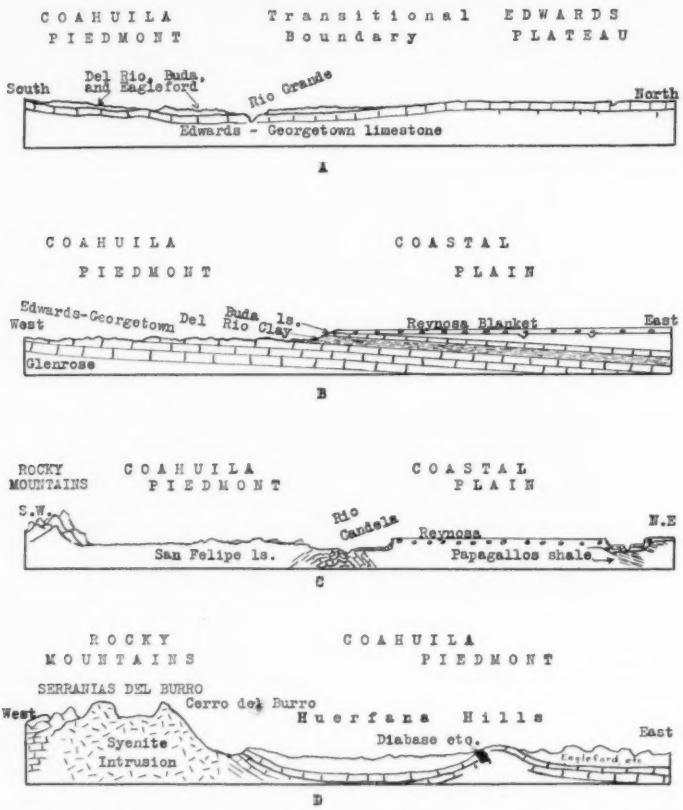

FIG. 7.—Four generalized profiles showing the boundary types between the Coahuila Piedmont and adjacent provinces.

A. The change from north (Edwards Plateau) to south occasioned by structure, as the more or less flat Edwards-Georgetown limestone of the Plateau dips into the Huerfana Basin. The principal topographic change is due to the presence of the higher Cretaceous beds, Del Rio, Buda, and Eagle Ford, in the Basin.

B. The boundary type in the neighborhood of San Carlos, south of the San Diego River.

C. The boundary type a few miles north of Lampasos. The boundary is the mesa front of the Reynosa conglomerate blanket, and has little relation to Cretaceous structure.

D. The boundary of the Coahuila Piedmont and the Rocky Mountains at Loma del Burro west of the Huerfana Hills. Compare with Figure 5, which shows relation where folding of the mountain flank is not complicated by intrusion.

thus attained is identical in character with that in the Coahuila Piedmont in Mexico between the Coastal Plain and the Burro Mountains (Serranias del Burro). Some distance south of the Rio Grande toward the southerly edge of the Huerfana basin, the Comanchean limestones again come to the surface, but here different drainage and structural conditions prevent the resumption of Edwards Plateau type of topography. There is no plateau. Instead, there is a gently rolling swell, in some places representing structure, and in others representing interruptions in minor physiographic cycles; or, merely, erosion by consequent streams.

From the Rio Grande for nearly a hundred miles southerly, the Coahuila Piedmont is bordered on the west by the Serranias del Burro, the easternmost topographic expression of Rocky Mountain structure. The sierra is a broad anticline nearly 100 miles long, consisting of Comanchean limestones and shales capped by the massive Edwards-Georgetown limestone. In it are numerous laccolithic and other intrusions of various rock, principally basic, but in cases approximating quartz-monzonite (Colorado Peak), and even syenite (Cerro del Burro). To the southeast on a prolongation of the axis of the Serranias del Burro lie the Peyotes Hills, which are also anticlinal. Possibly in structural classification of area, these hills should be included in the same province as the Serranias del Burro, but they are here separated because their topography is more similar to certain features in the Piedmont. The west border of the Piedmont, therefore, is considered to lie upon a topographic contour around the southward plunge of the Serranias del Burro; and the east border along the east and northeast flanks of the Peyotes Hills. The slight saddle between the Peyotes Hills and the Serranias del Burro is a drainage divide which separates the Piedmont into two sections: the Sabinas basin, and the Huerfana basin. The northern Huerfana–Del Rio section is drained by the Rio Grande, and the southern, Lampasos–Don Martin–Sabinas section, by the Salado River.

PHYSIOGRAPHIC HISTORY

Near the beginning of the Pleistocene, the last pre-Reynosa erosion cycle had reached the stage of maturity in northeast Coahuila and Tamaulipas. A mature rolling relief had been developed, and

the drainage pattern was intimately related to structure. This conclusion is reached by reconstructing the pre-Reynosa surface from the elevation of points at the bottom of the Reynosa gravels. The old drainage thus discovered is seen to be subsequent upon the known geological structure.

Then, rather suddenly, apparently, was inaugurated a period of relative depression, subjugating the area to rapid deposition. Extending as a mantel outward from the mountains was deposited the Reynosa formation These gravels gradually filled the mature val-

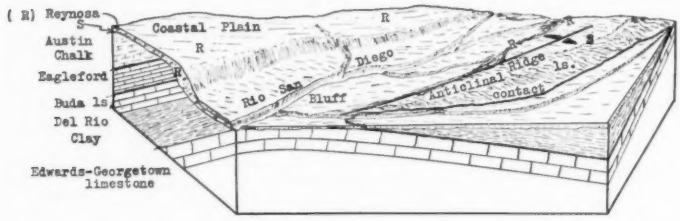

FIG. 8.—Block diagram illustrating physiographic history. Line *S* is mature, subsequent pre-Reynosa surface. Note that this line is low in the river channel, high on the anticlinal ridge to the right, and high again on the Coastal Plain to the left. The profile of line *S* thus indicates pre-Reynosa topography as subsequent upon the structure. The Coastal Plain is the depositional surface of the Reynosa. The river bluffs represent the intermediate Leona (?) stage; and the river channel, the present cycle. At the left front point of the diagram, the river is flowing upon the rediscovered pre-Reynosa surface.

leys until the pre-Reynosa topography was quite obscured. Then, by coalescence of the several valley deposits, the regional Reynosa surface appeared, forming an almost unbroken plain. The mature configuration of the pre-Reynosa (Pliocene?) surface explains, in certain localities at least, the variations in thickness of the Reynosa formation.

Again there was a change of process, and dissection of the Reynosa plain began. With penetration into the formation, structure again manifested itself, and streams were deflected to coincide with their buried channels, thus becoming subsequent by differential erosion between the soft Reynosa and the more resistant higher features of pre-Reynosa topography. But the Reynosa occupied the space vacated in the formation of the pre-Reynosa subsequent drainage sys-

tem. Hence, the streams, after being superimposed from the Reynosa surface, rediscovered their original Pliocene (?) courses. In places they are actually flowing at the lower Reynosa contact in channels determined near the close of the Pliocene, and with parts of a re-exposed fossil landscape near by. They are subsequent streams whose initial subsequence was determined in pre-Reynosa time.

Fluviatile deposition later took place, probably near the close of the Pleistocene, through a period sufficient for the formation of clay and silt deposits 30–50 feet thick. These clays in the Salado and San Diego rivers occur as terraces and never attain sufficient thickness to coalesce into a regional blanket as did the Reynosa. They may be equivalent to the Leona or Beaumont clays of Texas. Erosion was then resumed. The clays were dissected and meanders intrenched, until, with only minor interruptions, the present topography was attained.

It seems probable that some of the gentle folds which influenced pre-Reynosa topography are older than Rocky Mountain orogeny. This seems evident because, while the pre-Reynosa drainage was subsequent, the Rio Grande, for example, is antecedent across the Rocky Mountain uplift.

For purposes of comparison, and as suggesting similarity of Pliocene-Pleistocene conditions in widely removed sections of the Rocky Mountain border region, the physiographic histories of the Colorado Piedmont and the Coahuila Piedmont are tabulated side by side.

Colorado	*Coahuila*
Flat-top peneplain	Mature land surface upon which the Reynosa was deposited
Rocky Mountain peneplain; depositional surface of the High Plains	Depositional surface of the Reynosa
Park stage	Terraces of the Leona (?) stage

ADJACENT PROVINCES

Only brief consideration is given to the physiographic provinces which border the Coahuila Piedmont.

ROCKY MOUNTAINS

The following mountain groups in Mexico may all be regarded as parts of the great Rocky Mountain system: Serranias del Burro, Sierra del Carmen, Sierra de la Iguana, and the Sierra Madre Oriental.

Sierra Madre Oriental.—The Sierra Madre Oriental is a mountain group the most conspicuous feature of which is the famed "Sierra Madre Front." From near Lampasos southward for hundreds of miles, the Sierra Madre Front rises as a majestic east-facing battlement at the western edge of the Coastal Plain. Such minor foothills as the Sierra de la Iguana are scenically incomparable to the main Front.

Some 20 miles southwest of Lampasos, west of the Candela valley, is the rugged mountain massif of El Carrizal. This is a high mass of intrusive rock resembling monzonite-andesite porphyry. At the contact of the intrusive with the limestone occur contact metamorphic deposits of the Cia Fundidora de Fierro y Acero de Monterey. The deposit is characterized by crystalline and massive garnet, magnetite, epidote, pyrite, some chalcopyrite, hematite, calcite, and quartz.

The Carrizal massif is the northern knot of the great Sierra Madre Front. Northwest of Carrizal the Sierra Madre Oriental loses the unified identity of the Sierra Madre Front and becomes a number of more distinct ranges. At the north foot of the Carrizal knot lies the Mesa de Cartujano which is in the southern part of the Coahuila Piedmont.

Sierra del Carmen.—The ranges, which combined form the composite mountain front northwesterly from the Carrizal knot, extend to near Musquiz, north of which the mountains again attain unification in the rugged and serrate Sierra del Carmen which continues across the Rio Grande into Texas. The Sierra del Carmen is more closely related to the Rocky Mountain group of Texas than to the Sierra Madre Oriental.

Sierra de la Iguana.—The northern tip of the Sierra de la Iguana touches the southern tip of the Coahuila Piedmont at Lampasos. The Sierra is a long anticlinal foothill mountain ridge with flanks of San Felipe limestone, and a core of massive bedded blue-gray Tamaulipas—Edwards-Georgetown limestone. It contains a few mineral-

ized areas. Oxidized lead ore, probably of the replacement type, is shipped by wagon and burro from the El Refugio mine. The main line of the National Railways of Mexico, from Laredo to Monterey, rounds the northern tip of the Sierra at Lampasos and continues southward between the Sierra de la Iguana and the Sierra Madre Front.

Serranias del Burro.[1]—The Serranias del Burro are a rugged mountain group formed by the dissection of a great anticlinorium capped by massive Edwards-Georgetown limestone. The extent is shown on the map.

FIG. 9.—View in the Serranias del Burro, a few miles north of Colorado Peak

Beneath the caprock limestone occur softer limestones and shales of the Glenrose formation, and this sequence has given rise to an arching mesa type of extremely rugged topography. At various points throughout the mountains occur igneous intrusions of syenite, quartz monzonite, andesite (?), and diabase. The small amount of metamorphism in the limestone at the contact with these intrusions seems remarkable. The contact is well exposed in a number of places, and invariably the only alteration is a slight recrystallization due to heat. Often limestone within 3 feet of a contact is unaltered.

[1] Although various names have been applied to these mountains, the writer here follows the nomenclature established by Jorge L. Cumming in "Reconocimiento geologico-petroleo de la parte norte del Estado de Coahuila," *Folleto de Divulgación Num. 29* (July, 1928). As this is a publication of the Instituto Geologico de Mexico, the nomenclature of Mexican geography therein sanctioned should be followed.

Because of the barren and rugged nature of the mountains, they support almost no population. Ranches occur in some of the larger valleys where wells and springs provide water for domestic use and stock, but a large part of the mountainous area is waste land. Because of this, one cannot fail to appreciate the contrast of the beauty and freshness of some of the more fortunate areas such as the circular valley around the intrusive Colorado Peak, the springs near San Augustin Peak, and the rose garden of the Hacienda San Miguel.

The Serranias del Burro continue into Texas, but become lower and less rugged north of the Rio Grande and gradually merge into

FIG. 10.—View of the Coastal Plain near the Salado Arch. The flat Reynosa surface merges with the gently undulating Papagallos (Taylor-Novarro) shale topography.

the hills and table-lands of the southeast border of the Marathon basin. In the Big Bend country of Texas north of Stilwell crossing (a mountain-enclosed cauldron of intense heat and aridity in midsummer)[1] is exposed an excellent view of the northward thinning Comanchean-Cretaceous strata, resting on the beveled surface of the Jurassic peneplain.

THE COASTAL PLAIN

The Mexican Coastal Plain consists of three vaguely defined units. From the Gulf as far inland as the town of Reynosa on the Rio Grande, is the fairly flat part. Then, inland, from Reynosa to the Ceja Grande, is the gently undulating rolling area of Tertiary sandstones. Considerable lattice drainage has developed in this belt, especially to the west. The formations dip, on the whole, gently

[1] In this apparent waste land grows the Candela plant from which is extracted much of the wax used in phonograph recording.

gulfward, though there are structural irregularities in such areas as the Guerrero dome and the Roma dome now being prospected for oil, the Aldamas anticline, and others. The Ceja Grande, shown on the map (Fig. 4), is a prominent topographic ridge which is the outcrop of the basal Tertiary sandstones. Rocks of the Ceja Grande dip more or less northeasterly at angles of about 10–20°.

Westerly from the Ceja Grande is the Upper Cretaceous outcrop, and west of this unit is the Coahuila Piedmont. Much of the topography west and northerly from the Ceja Grande is gently rolling or flat, as the exposed rocks are principally shale. Great portions of this belt are covered by as yet undissected plains of the Reynosa blanket. Such areas merge with the gently undulating shale topography so that the general effect is of a single vast plain. The flat plain is particularly conspicuous in the area of San Carlos, Piedras Negras, Allende, and to the southeast.

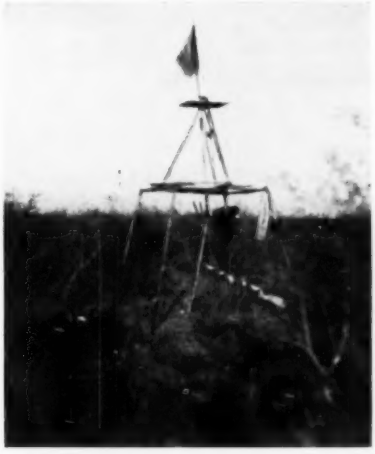

FIG. 11.—Portable plane-table standard used in the thick brush areas.

A large portion of the Coastal Plain is covered by thick brush which makes exploration difficult. Figure 11 shows a portable plane-table standard designed by the writer for surveying in the brush. The platform, which was carried strapped to the running board of the car, could be erected in less than five minutes, and when set up, permitted an unobstructed view of most of the horizon from a height-of-instrument of from 10 to 14 feet above the ground, according to the adjustment of the telescopic legs.

In the Coastal Plain as in the Coahuila Piedmont, there is evidence of the mature surface of subsequent topography upon which the Reynosa was deposited. A few miles downstream from where the Laredo-Monterey line of the railroad crosses the Salado River, the

base of the Reynosa is exposed resting upon Cretaceous shale in a syncline in the bed of the river. Yet a few miles northeast, on the Salado Arch the contact of the Reynosa with Cretaceous shale is exposed in the hills several hundred feet higher in elevation, showing the approximate coincidence of present drainage and pre-Reynosa subsequent topography. Still farther northeast, on the Ceja Grande, patches of Reynosa occur on the tops of the sandstone ridges; and huge potholes, now high up on the Ceja, give evidence of the swirling torrent that deposited the Reynosa conglomerate. The water marks in these old potholes are level at the present time, showing that the region has been subjected to very little tilting since the period of Reynosa deposition.

AN EARLY PRE-CAMBRIAN SEDIMENTARY SERIES IN NORTHERN QUEBEC[1]

CARL TOLMAN
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ABSTRACT

Attention is drawn to a thick series of altered sediments which occur conformably within the Keewatin volcanics in northern Quebec. The conformable relation of the sedimentary series to the volcanics is one of its chief points of interest. The rather exceptional lithological nature of the sediments is described, and the probable conditions of deposition discussed. Correlation with other occurrences of early pre-Cambrian sediments in northern Quebec is attempted. Other sedimentary series, thought to be of Keewatin age, in Ontario and Quebec are briefly considered.

INTRODUCTION

General statement.—The writer in 1929 carried on reconnaissance-mapping for the Geological Survey of Canada in the region of the Obatagamau River, northern Quebec,[2] followed in the same region in 1930 by more detailed mapping of the Opemiska quadrangle.[3] As a part of this work there was mapped a series of sediments, here called the Opemiska series, whose petrographical character and structural relations with regard to other members of the pre-Cambrian succession are thought to be of sufficient general interest to warrant this note. The sediments were only studied and mapped in any detail in the Opemiska quadrangle, but the reconnaissance work and reports from prospectors indicate the wide extent of the sediments to the west along their strike.

Location.—The Opemiska quadrangle, Abitibi County, Quebec, bounded by parallels of latitude 49°45′ and 50°00′ north and meridians of longitude 74°30′ and 75°00′ west, lies about 300 miles almost due north of Ottawa or about 150 miles north of the Quebec-Coch-

[1] Published by permission of the Director of the Geological Survey of Canada. Petrographical work, some of which is involved in this article, was aided by an allotment from the grant made in 1930 by the Rockefeller Foundation to Washington University for the support of research in science.

[2] "Obatagamau River Area, Abitibi Territory, Quebec," *Geol. Surv. Can. Summ. Rept.*, Part C (1929), pp. 20–33.

[3] "Southern Part of the Opemiska Map-Area, Quebec," *Geol. Surv. Can. Summ. Rept.*, Part D (1930), pp. 22–49.

rane line of the Canadian National Railways. It is situated west of the Chibougamau district which has received more or less attention from the prospector and mining promoter for a number of years. The quadrangle can be reached by a number of canoe routes from points on the Canadian National Railway. The most widely used of these is that from Oskelaneo which follows the route into Lake Chibougamau for most of the distance. There is a winter road from St. Felecien, Lake St. John, by way of Lake Chibougamau. However,

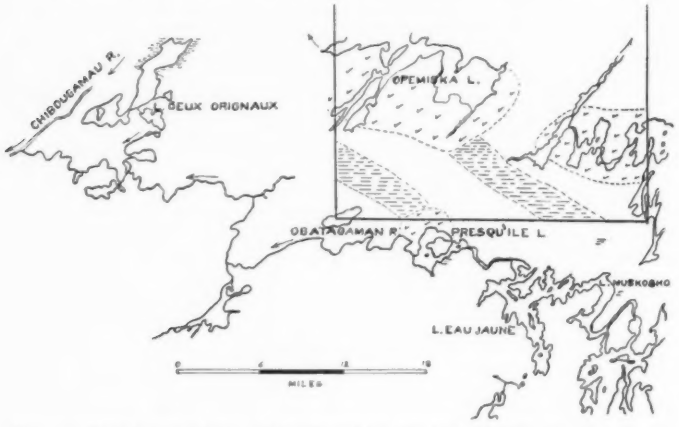

FIG. 1.—Sketch map of part of the Opemiska district including the southern part of the Opemiska quadrangle. Lined areas represent Opemiska sediments.

during the recent years airplane transportation from several towns on the Canadian National Railway to a great extent superseded other methods of transportation into the area for both passengers and freight.

General character of the district.—The Opemiska quadrangle near its center contains Lake Opemiska, a prominent unit of the Chibougamau drainage system, after which the quadrangle is named. The Opemiska district or region refers to a larger area of indefinite size centered at Lake Opemiska. This region lies well within the Canadian Shield and has the general topographic character of that great area. The elevation above sea level of Lake Opemiska is about 1,032 feet. Throughout much of the area the relief can be measured in

tens of feet. A prominent range of ridges and hills stretches east-west along the north shore of lakes Chibougamau, David, and Simon, but frays out westward in the Opemiska quadrangle with the occurrence of a few relatively isolated hills rising as much as 600 feet above the general level.

Over one-third of the region is occupied by lakes, and a fairly large part of the remainder is low, flat, swampy, and practically devoid of outcrop. Other areas of more relief occur where the bed rock is obscured by deposits of morainal and outwash material. In some localities outcrops are relatively isolated in swamp, moraine, or sand plain and typically constitute elevations, commonly low but ranging upward to prominent hills. Elsewhere outcrops are closely spaced or essentially continuous over a considerable area and occur as low rocky elevations separated by depressions occupied by swamps, lakes, or streams. The shore lines of some of the lakes and streams afford good rock exposures especially at times of low water.

GENERAL GEOLOGY

The oldest rocks of the Opemiska district are a great series of altered volcanics which occur widely in this part of Quebec and are locally known as the Abitibi volcanics. They are generally regarded as Keewatin, in that they constitute the base of the recognized pre-Cambrian succession and are of a type similar to those occupying a like stratigraphic position elsewhere on the Shield. They are all considerably altered. Many of the flows show well-developed pillow structure. Andesites appear to have been by far the most common rock type represented. Appreciable amounts of the common, more acid, and more basic volcanic types are represented, as well as minor amounts of volcanic fragmental materials. This basal series of volcanics is of particular interest in the Opemiska district because there it appears to include, conformably within it, a thick series of moderately altered sediments, namely, the Opemiska series. In the present study the volcanics and the sediments together are referred to as the schist complex.

The old volcanics and associated Opemiska series are intruded by much igneous material as dikes, sills, and bodies of more equidimensional cross-section, ranging in width from a fraction of a foot to half

a mile or more. They appear to represent rock types ranging from diorite through diabases and gabbros to peridotites. All have suffered considerable metamorphism typically without the development of much schistosity, and, to a large extent, are now composed essentially of varying proportions of hornblende and rather sodic plagioclase, and have their original textures more or less obliterated. They are of at least two different ages. The most widely occurring type is

TABLE OF FORMATIONS

QUATERNARY		Peat, clay, silt sand, gravel and unsorted morainic material
PRE-CAMBRIAN	Dioritic and diabasic intrusives	Dikes, may in part be lamprophyres
	Granitic intrusives	Opemiska granite Presqu'ile granite Chibougamau complex
	Intermediate and basic intrusives	Metamorphosed diorites, diabase, gabbros, and peridotites
	Schist complex	Upper Volcanics: metamorphosed acid to basic flows and pyroclastics Opemiska Series: metamorphosed arkose, conglomerates and minor amounts of greywacke, slate, and limestone Lower Volcanics: metamorphosed acid to basic flows and pyroclastics

one which now resembles very closely the altered andesite flows of the Abitibi volcanics that do not show pillows or an appreciable development of flow structure.

The old volcanics with the Opemiska series and the later basic intrusives are intruded in different parts of the district by large masses of granitic rock. It is probable that they do not all belong to the same epoch of intrusion although, in general, this cannot be determined definitely because of the separation of the different masses. Some of the masses are made up of two or more rock phases which, in some cases at least, probably represent separate, but closely related, intrusions. The rock types represented range from altered anorthosite and associated rocks, which extend westward from the

Chibougamau district into the Opemiska district, to biotite granite, hornblende granite, and syenite.

Some diabasic dikes, commonly less than 50 feet wide, cut some of the granite bodies. The writer at the present time is not prepared to say whether they are satellitic to the granitic masses or whether they represent a more generally distributed late pre-Cambrian series of dikes analogous to the olivine diabase dikes so prevalent north of Lake Huron.

STRUCTURE

An axis of a closely folded anticline trends south 70° east across the southern part of the Opemiska quadrangle. Reconnaissance work indicated that the same type of structure persists at least as far west as Lake Deux Orignaux. Southeast of the Opemiska quadrangle the structure becomes more complex. In this direction the axis of the anticline plunges sharply. Prominent north-south cross folding, probably accompanied by some cross faulting, is indicated.

OPEMISKA SERIES

Importance.—In the Opemiska district the sediments, here called the Opemiska series, occur within the great series of volcanics generally referred to the Keewatin and separate it into lower and upper divisions. The chief interest of the sediments is centered in their conformable relations to the underlying and overlying volcanics and in their rather exceptional lithologic character as shown in the Opemiska quadrangle.

Distribution and thickness.—The sediments were mapped as two roughly parallel bands each about 2 miles wide and about $3\frac{1}{2}$ miles apart, extending approximately south 70° east across the southern part of the Opemiska quadrangle. The bands represent the outcropping edges of the same formation on the two sides of an eroded anticline. The dips are essentially vertical and over 10,000 feet of sediments appear to be represented.

The sediments appear to extend westward for a considerable distance beyond the boundaries of the quadrangle. They were encountered by the writer on the shores of Lake Deux Orignaux along their strike about 15 miles to the west.[1] Prospectors report the occurrence

[1] C. Tolman, "Obatagamau River Area, Abitibi Territory, Quebec," *Geol. Surv. Can., Summ. Rept.*, Part C (1929), p. 26.

of similar sediments yet farther west, on the shores of a large unnamed and unmapped lake west of the Chibougamau River. Little is known regarding their extension southeastward beyond the Opemiska quadrangle. A metamorphosed rock suggesting derivation from sediments occurs on the south shore of Lake Presqu'ile and may represent the southeastern extension of the southern band beyond the Presqu'ile granite mass. The northern band was picked up south of the Opemiska quadrangle on the canoe route between Lake Leddon and Lake Eau Jaune. Still farther southeast metamorphosed sediments probably belonging to this band were noted near a granite contact just east of Lake Muskosho. A further southeasterly extension has not been noted.

In the Opemiska quadrangle the anticline, on the two eroded sides of which the sediments outcrop, plunges sharply toward the southeast. The plunge becomes even more pronounced farther southeast in the region of the west side of Lake Eau Jaune. Here a prominent north-south cross-fold is indicated. This may be accompanied by some faulting. Only volcanics in addition to intrusive bodies appear to be exposed in this locality. There are large areas poor in outcrop. It seems most probable that the plunge has been sufficient to carry the sediments beneath the present surface, and the volcanics outcropping here are those stratigraphically overlying the sediments.

Relation of adjacent volcanics.—No structural discordance whatever was noted between the Opemiska series and the underlying and overlying basal volcanics. There appears definitely an interbedded relationship. At the base of the sediments there is a transition zone from the lavas into the sediments at least 2,000 feet wide which in its lower part consists of altered lavas predominantly of intermediate basicity with minor amounts of interbedded sediments. Farther up, the sediments increase until they constitute the predominant rock with few interbedded, altered, intermediate flows. The major portion of the sedimentary series contains little if any interbedded volcanic material. However, throughout, parallel to the structure, there are a few small bodies of altered igneous material whose field relations and general character do not indicate whether they represent altered sills of the dioritic and gabbroic intrusives or altered massive flows. The interbedded relationship between the altered sediments and the

altered lavas is also shown at the upper contact of the sediments, although it is not so wide as that shown at the base of the sediments. Just above the sediments is considerable volcanic fragmental material, much of which was waterlaid. This passes upward into altered andesitic lavas, much of which is characterized by splendidly developed pillow structure.

Composition.—The sediments consist predominantly of coarse clastic material. Feldspathic arkose, grits, and conglomerate are the most common rock types. Minor amounts of greywacke were noted. Very little argillaceous material appears to be present, and only two narrow bands of limestone were encountered. The most prominent characteristic of the rocks, as a whole, is their highly feldspathic nature. The grain of these rocks varies from very fine, as of silts, through medium and coarse grain to felspar grits and conglomerate. Also a striking characteristic is a general lack of sizing of the constituent particles of the different beds of the various members of the formation. A well-developed stratification is not general, although in most places there is at least a certain amount of coarse bedding. In the arkose this commonly results from the presence at intervals of lenses of grit or conglomerate. In the fine-grained types which occur only in very minor amounts, the stratification tends to be fine, and among the very fine in grain delicate lamination may be present.

A highly feldspathic fine- to coarse-grained arkose is by far the most dominant rock type; much of it could be called a grit. This rock type is estimated to comprise over 70 per cent of the total sediments. Its weathered surface is distinctive in that it is markedly white in color and is composed of bleached kaolin-like material resulting from the weathering of the feldspar. Freshly broken surfaces vary in color from a light gray to a very dark gray or practically black and some have a slightly greenish cast. Glistening feldspar cleavage faces are conspicuous on the fresh surfaces of most specimens. Some resemble markedly a syenite poor in dark mineral. Under the microscope poor sizing of the constituents in much of the arkose is particularly marked. A considerable number were examined in thin section. Most typically the rock is composed of 90–95 per cent feldspar of which one-sixth to one-half is present in subangular particles from 1 to 2 millimeters in longest dimensions dis-

tributed at random in a feldspathic ground mass made up to particles .01–.05 millimeters in diameter. From 10 to 50 per cent of the larger feldspar particles show albite twinning. No microcline twinning was observed. No feldspar indices of refraction appreciably above that of balsam were noted. Quartz rarely exceeds 5 per cent of the rock and may be present in both large and small particles. There is practically a total absence of dark minerals. Some fine silt-like varieties occur also, composed of feldspar particles. In the feldspar grits, a common variant of the feldspathic arkose, random particles up to 5 millimeters in longest dimension, largely of feldspar but with, in places, some quartz, may be present in a matrix composed essentially of feldspar particles less than 1 millimeter in diameter. No typical quartzite was noted anywhere in the section.

Conglomerate are next in abundance to the arkose. They are distributed widely throughout the section. Practically continuous outcrops of conglomerate as much as 400 feet across the strike were noted. The content of pebbles, cobbles, and boulders is variable from place to place. There may be square yards with only one roundstone,[1] and very rarely do they exceed the matrix in amount. The most typical occurrence is a sparse distribution of roundstones throughout an arkose or grit matrix. Roundstones were noted with diameters ranging from a fraction of an inch to as much as 2 feet. Probably those with diameters in the neighborhood of 5 inches are the most common. Those of granitic rocks appear rather well rounded; whereas the few noted of greenstone and slatey material tend to be inequidimensional. Some of them may have been elongated by deformation. The roundstones are predominately granitic, of which most are syenites poor in dark minerals. True granites are remarkably scarce among the roundstones within the Opemiska quadrangle. The character of the pebbles was carefully noted, and specimens of the different types were collected and studied in thin section. Most are varieties of syenite, flesh to gray in color, and fine to coarse in grain. Most are equigranular, but some are porphyritic. No feldspar with an index appreciably above that of balsam was noted. The

[1] F. A. Fernald, "Roundstone, a New Geologic Term," *Sci.*, Vol. LXX (1929), p. 240. In the article quoted, the term "roundstone" is proposed to include the two or more sizes of rounded stones that may occur in a conglomerate.

relative proportions of albite and potassium feldspar vary considerably in different specimens. Some specimens are made up predominantly of potassium feldspar, in some cases showing no microline twinning and in others showing amounts ranging up to 25 per cent. Others were noted composed predominately of albite (Ab 93+An 7). The majority, however, show varying proportions of albite and potassium feldspar. About 5 per cent of quartz is present in most slides, and apatite and zircon were noted as accessories. In some slides very small amounts of chlorite, apparently after some original ferromagnesian mineral, is present. Other pebbles noted in very small numbers comprise chlorite schist, slate, metargillite, diorite, quartz feldspar porphyry, and hornfels.

A few narrow beds of slate were noted, some of which showed fine lamination. Also a small amount of sheared greywacke was encountered. A little graphitic schist was found in one locality. Two bands of limestone with greatest exposed width of 50 feet were noted. From its reaction with acid the rock appeared to be dolomite.

No syenite terrane such as must have served as the source for the syenitic materials of the conglomerates and the preponderant feldspar of the feldspar arkose has so far been recognized in the district.

Conditions of deposition.—The bulk of the rocks comprising the Opemiska series in the Opemiska quadrangle are of marked interest on account of their highly feldspathic nature. Such rocks are considered rare.[1] From a consideration of the character of these rocks, as far as known, some inferences can be made regarding the probable conditions of their formation. First, the sediments must have resulted predominantly from the disintegration of a syenitic rock relatively poor in dark minerals. This emphasizes their exceptional nature, for purely syenitic terranes of any considerable size are rare. Syenitic bodies commonly are phases of larger granitic intrusions and where they do occur as separate intrusions they tend to be small. It would follow also that conditions were favorable for the disintegration of the syenite without extended accompanying decomposition of the feldspar and that transportation and deposition of the disintegrated material went on with sufficient rapidity and in such

[1] D. C. Barton, "The Geological Significance and Genetic Classification of Arkose Deposits," *Jour. Geol.*, Vol. XXIV (1916), p. 418.

a manner that the feldspar particles were imperfectly sized and remained relatively unaltered; as a result, the sediments are not characterized by a normal sandstone-shale alternation but by poorly sized, relatively fresh feldspathic arkoses, grits, and conglomerates.

Barton concluded that the geological significance of arkose[1] "varies from case to case and cannot be limited in the general statement to significance of a special set of conditions." Further, that arkoses are not necessarily formed under rigorous climatic conditions, but may also result either directly or indirectly under moist and more temperate climates. The latter condition, however, would tend to produce much decomposition, so that the resulting arkose would contain appreciably altered feldspars commonly in an argillaceous matrix derived from more easily decomposed grains of feldspar and other silicates and may be associated with argillaceous beds resulting from the totally decomposed parts of the rock.

In the light of Barton's conclusions and bearing in mind the highly feldspathic nature of the Opemiska arkose and the relative unaltered nature of its constituents, it would appear that the climate under which the arkose was deposited must have been rigorous, but the particular nature of the climate and of the conditions of deposition are not so clear. In the writer's opinion, the most reasonable conditions would be those of an arid region. Here the sediments are conceived as having been derived from a syenite area of at least appreciable relief. Weathering would consist largely of mechanical disintegration on bare rock surfaces. Most likely the transportation of the débris would be largely accomplished by water acting during the infrequent periods of heavy rainfall characteristic of some arid regions and to some extent by the movement of the material down hillsides under the influence of gravity. Marine conditions are thought to have prevailed adjacent to the syenitic terrane, and in this environment a large part, at least, of the sediments are thought to have been deposited. Some, at least, may be terrestrial. If the submarine origin for the pillow structure of the lavas is admitted, the marine origin of the arkose receives additional support, in that typical beds of arkose occur interbedded with lavas of which some show pillow structure.

[1] *Ibid.*, p. 448.

The sediments as exposed in the Opemiska quadrangle, as has already been indicated, were apparently derived from a relatively homogeneous terrain of syenitic rock. As such terranes existing on the earth's surface at the present time tend to be small, it would appear that the disintegrated material, accumulated to form the Opemiska sediments of the Opemiska quadrangle, was gathered from a relatively local area. Support for this contention is obtained from the fact that the particles of feldspar, the predominant constituent of the rocks, indicate by their lack of sizing and relatively little alteration that they were not subjected to prolonged transportation. This points to the significant conclusion that the lithology of the sediments may be expected to become notably different as they are followed away from the Opemiska quadrangle, even though they may have been deposited under the same conditions and in an identical environment. The terrane from which the sediments had been derived would be different, and with this there would be a change in the lithology of the sediments. Because of the rather exceptional nature of the sediments in the Opemiska quadrangle, this change might well be marked and would most probably be in the direction of a normal arkose with greywacke and conglomerate containing a greater variation of plutonic rock pebbles. Of course, with these changes there may well be others in the sediments due to differences in the environment of deposition, such as the change from near to off-shore conditions and so forth, or to changes in the conditions of deposition, probably, of more regional nature, such as climate or the topographic nature of the terrane suffering erosion.

The probable change in lithology of the Opemiska series beyond the Opemiska quadrangle is an important point to keep in mind when attempting correlation of the sediments from place to place.

Alteration.—The degree of alteration of the sediments varies considerably from place to place, but only in the fine-grained varieties is it marked. In them the feldspars may be greatly sericitized and any original ferromagnesian minerals altered to chlorite. Epidote and calcite are commonly present. In the medium- to coarse-grained arkosic types, which constitute the bulk of the sediments, the alteration is very much less. In thin section under the microscope, they appear in most cases relatively fresh. Some fine sericite, epidote, or

zoisite may be developed in the feldspar, and a variable amount of carbonate may be present.

A certain amount of schistosity is perceptible throughout, but except locally it is only marked in the fine-grained varieties. In general, the conglomerate pebbles have not been elongated parallel to the schistosity by deformation, although locally the appearance of some of the relatively rare greenstone and slaty pebbles suggests that they may have been so affected. The matrix, especially when fine-grained and locally where coarse-grained, shows schistosity which, when intensely developed, appears wrapped around the pebbles.

OTHER EARLY PRE-CAMBRIAN SEDIMENTARY SERIES IN NORTHERN QUEBEC

In the Chibougamau quadrangle about 15 miles east of the Opemiska quadrangle there is a series of sediments unconformably overlying the volcanics, dioritic intrusives, and granites.[1] The sediments are cut by quartz veins; so younger granites probably are present, but so far have not been recognized. They consist largely of conglomerate with sandstone, arkose, slate, and argillite and have been tentatively regarded as of Huronian age. Most occurrences are flat lying, but in some places they are described as dipping steeply. The described stratigraphic position and attitude of these rocks precludes correlation with the Opemiska series. However, some slate in the Chibougamau quadrangle at the mouth of Lake Bourbeau was included tentatively in the Keewatin by Retty.[2]

H. C. Cooke[3] has rapidly examined considerable territory in northern Quebec by reconnaissance methods and has described a number of occurrences of altered pre-Cambrian sediments. It is of importance, therefore, to consider these occurrences in an effort to correlate the Opemiska series with them. Cooke correlates these scattered

[1] Chibougamau Mining Commission, "Geology and Mineral Resources of the Chibougamau Region, Quebec," *Rept. Dept. Col. Mines and Fisheries*, Quebec (1911), p. 118 ff.; J. B. Mawdsley, "Lake David Area, Chibougamau District, Quebec," *Geol. Surv. Can., Summ. Rept.*, Part C (1927), p. 11; J. A. Retty, "Township of McKenzie, Chibougamau Region," *Ann Rept., Quebec, Bur. of Mines* (1929), p. 57.

[2] J. A. Retty, *op. cit.*, p. 50.

[3] H. C. Cooke, "Some Stratigraphic and Structural Features of the Pre-Cambrian of Northern Quebec," *Jour. Geol.*, Vol. XXVII (1919), pp. 65, 180, 263, 367.

occurrences, that he examined, into two series, one of which he called the Mattagami series and the other the Nemenjish series. From the nature of the work, observations were necessarily hasty and in some cases few in number, and the correlations were not considered beyond question, as the sediments were found "merely as comparatively small remnants separated by wide areas of intrusive granite." The criteria used in correlation were necessarily limited to the following: (1) petrographic similarities, (2) similar geological succession, (3) similar deformation, (4) similar relations to older and younger formations.

MATTAGAMI SERIES

This series is made to include the sediments of the Mattagami area and the Pontiac, Broadback, Lucky Strike, and Brock series and is held to overly the basal volcanics with an erosional unconformity. The Sediments are described in the different areas as composed of a basal conglomerate which may be as much as 300 feet thick, followed by beds of arkose and greywacke, in places grit, and at the top a mica or hornblende sedimentary schist. Of the occurrences of the Mattagami series only that in the Brock area (Brock series) is in the neighborhood of the Opemiska quadrangle. It lies about 15 miles to the northeast and is thought to represent the north limb of an east-west trending anticline, though outcrops are poor in this locality. The top of the sediments is cut off by a granitic intrusion. The succession in the Brock area is given in order of age as follows:

Mica and hornblende schists
Grits and impure sandstone
Conglomerate
Unconformity
Green schist and basalts

In the conglomerate the pebbles preponderate greatly over the matrix, which is an impure sand. "About 30 per cent of the pebbles are hornblende granite; the remainder are various basic rocks, now so sheared that their original composition is indeterminable." About 25 miles to the southwest, on the Chibougamau River near the mouth of the Obatagaman River, Cooke noted another wide area of rocks similar to the upper beds of the Brock series, but the conglom-

erate was not found here and for this reason Cooke suggested that they may not belong to the Brock series, but may be fine-grained sediments of the Nemenjish series. The occurrence is on the strike of the Opemiska series about 20 miles west of the Opemiska quadrangle and only 3 miles west of the sediments noted by the writer on Lake Deux Orignaux.

NEMENJISH SERIES

This series of altered sediments, mapped about 20 miles southeast of the Opemiska quadrangle, is, according to Cooke, made up of interbedded garnetiferous and nongarnetiferous mica gneiss, hornblende gneiss, and crystalline limestone. At the base, the mica gneiss occurrs interbedded with tuffaceous sediments. This series is held to overlie the volcanics with no structural nor erosional discordance, "although this determination is weakened by the fact that the contact was observed at one place only." The upper contact of the series wherever noted by Cooke was with a younger granite. The structure is that of an east-west monocline dipping to the south, produced by repeated strike faulting. Cooke correlates these sediments with the Grenville series to the south.

CORRELATION OF OPEMISKA SERIES AND NEMENJISH SERIES

The Opemiska series resembles the Nemenjish series as described in the original locality in that both at their base are conformable with the volcanics. Unfortunately the upper contact of the Nemenjish series wherever observed by Cooke was with a later granitic intrusion. The Opemiska series is conformable with overlying volcanics. There are, however, some important differences in lithology, the most important of which is occasioned by the apparent small amount of conglomerate in the Nemenjish series and its prevalence throughout the Opemiska section. It is conceivable that, under the influence of dynamic and igneous metamorphism, such feldspathic arkoses and other fine- and medium-grained sedimentary types characteristic of the Opemiska series could be converted to the various gneisses which, according to Cooke, are characteristic of the Nemenjish series; but one would expect traces of such conglomerates as are so prominent in the Opemiska series to persist in the resultant gneiss particularly when sedimentary bedding can be observed in the

Nemenjish series. It is true that Mawdsley[1] mentions conglomerates in the Nemenjish series, but does not indicate their relative amount. It would seem then that a definite determination of the relation between the Opemiska and Nemenjish series is not possible at this time, but must await further work particularly in the Nemenjish area and areas intermediate between it and the Opemiska quadrangle.

As to the Mattagami series of the Brock area (Brock series) it would seem that, although lithologically these sediments appear to resemble the Opemiska series, definite correlation of the two is precluded by Cooke's determination of the unconformable relations between the Brock series and the underlying volcanics. However, it seems highly probable that the occurrence of sediments on the Chibougamau River above the mouth of the Obatagaman River, included tentatively by Cooke in the Brock series, is a part of the Opemiska series.

OTHER SEDIMENTS OF PROBABLE KEEWATIN AGE IN ONTARIO AND QUEBEC

Keewatin time is ordinarily pictured as a great period of volcanic activity on the Canadian Shield, and the extent to which sediments appear to be associated with the volcanics has probably not been sufficiently emphasized. Of course, it would be suspected that there would be such variation in the stratigraphic history in the Keewatin from place to place when one considers the length of time involved and the considerable area over which rocks of this age are found.

A certain amount of tuffaceous or other sediment is commonly associated with the Keewatin volcanics in most localities. However, in a few localities throughout the Shield the Keewatin volcanic activity was apparently broken by prolonged periods of sedimentation. Such localities in northern Quebec have just been discussed. It would probably be of interest to consider briefly other described localities in Ontario and Quebec. It is true that with regard to the relations in some of the localities there have been differences of opinion. The sedimentary localities may be grouped into three broad

[1] J. B. Mawdsley, "Eagle River Area, Abitibi Territory, Quebec," *Geol. Surv. Can. Summ. Rept.*, Part C (1927), p. 24.

areas for the purposes of this discussion,[1] (1) the region of southern Ontario and the southern Laurentian highlands of Quebec comprising the Grenville subprovince, (2) the broad region known as the

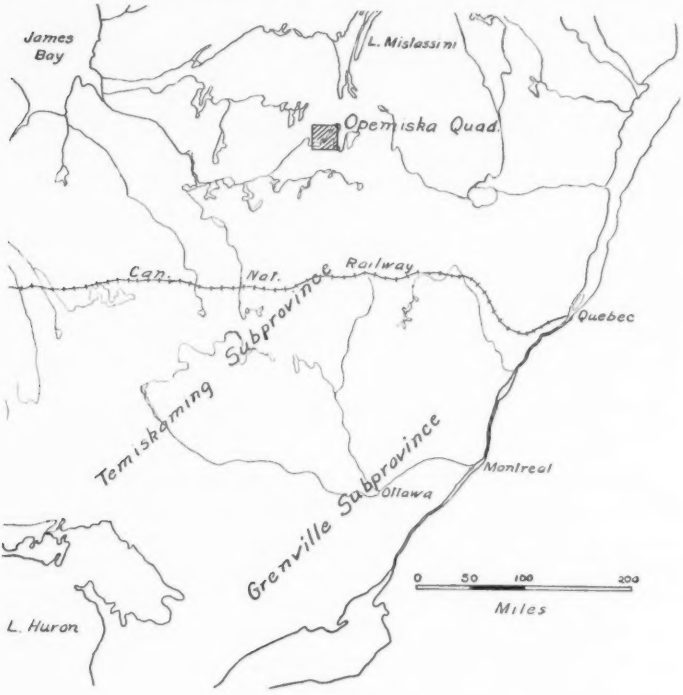

FIG. 2.—Index map

Temiskaming subprovince extending northeast from Lake Superior and Lake Huron to Lake Temiskaming, Rouyn district, and Lake Mistassini, (3) the region northwest of Lake Superior.

GRENVILLE SUBPROVINCE

The Grenville series, widespread in the region known as the Grenville subprovince in southern Ontario and western Quebec, is com-

[1] M. E. Wilson, "The Grenville Pre-Cambrian Subprovince," *Jour. Geol.*, Vol. XXXIII (1925), p. 389.

monly referred to the Keewatin, although such an age for it has not been definitely established. The Nemenjish series was correlated with the Grenville by Cooke on the basis of certain lithological features and its conformable relations to the basal volcanics.[1] However, large areas of batholithic intrusives separate the Grenville subprovince from the great area of pre-Cambrian rocks extending essentially continuously from north of Lake Huron northeastward through the Lake Temiskaming and Rouyn regions of northern Ontario and Quebec and including the area of the Nemenjish series. These intrusions have proved a great barrier to the correlation of the pre-Cambrian rocks of the two great areas. Conditions existing in the Lake Huron region suggest to workers in that locality that the Grenville series of the Grenville subprovince may possibly be of Huronian age.[2] On the other hand, work in the Rouyn and adjacent areas suggests that the Grenville can best be correlated with the pre-Huronian Keewatin or Temiskaming formations. Additional important evidence in support of a pre-Huronian age for the Grenville has recently been obtained from within the Grenville subprovince.[3]

The Hastings series, according to Wilson,[4] is confined to southeastern Ontario and is considered either as a local phase of the Grenville series[5] or a local formation of limited extent overlying the Grenville.

TEMISKAMING SUBPROVINCE

The rocks in this great area, excluding intrusive types, are referred to three major rock series. They are the Keewatin volcanics, the Temiskaming sediments, and the Huronian. In northeastern Ontario the Keewatin is overlain unconformably by the Temiskaming which in turn is overlain unconformably by the Upper Huronian Cobalt series. Farther east in Quebec the unconformable relations

[1] Cooke, *op. cit.*, p. 271.

[2] T. T. Quirke, "Correlation of Huronian and Grenville Rocks," *Jour. Geol.*, Vol. XXXII (1924), pp. 316–35; T. T. Quirke and W. H. Collins, "The Disappearance of the Huronian," *Geol. Surv. Can. Mem. 160* (1930).

[3] J. B. Mawdsley, "The Meach Lake Conglomerate," *Trans. Roy. Soc. Can.*, Vol. XXIV (1930).

[4] *Op. cit.*, p. 395.

[5] F. D. Adams and A. E. Barlow, "Geology of the Haliburton and Bancroft Areas," *Geol. Surv. Can. Mem. 6* (1910), p. 402.

between the Keewatin and the Temiskaming, though generally recognized, are not so conspicuous. In the Sudbury district, to the southwest, the Sudbury series has been generally considered to be equivalent to the Temiskaming series.[1] but its relations to the Huronian is not clear.[2] Lawson believes that the Sudbury series belongs in the Huronian and is not equivalent to the Temiskaming.[3]

In a number of localities in the Temiskaming subprovince there are sedimentary series conformably associated with the Keewatin volcanics. Continued geological work in this great area will no doubt show a yet wider distribution of these sediments. Of the sediments found in this subprovince the Nemenjish series and the Opemiska series have already been alluded to. Other sediments occurring intimately associated with the Keewatin volcanics within the subprovince are as follows: (1) a number of separate bodies in Rouyn-Harricanaw Region, Quebec; (2) the sediments of the Desmeloizes area in Abitibi district, Quebec; (3) the Ridout series in the Sudbury district of Ontario; (4) the Dore series in the Michipicoten district of Ontario; and (5) sediments on the northwest shore of Lake Superior.

ROUYN-HARRICANAW REGION[4]

A number of large bands of Keewatin sediment largely of tuffaceous character are mapped in Palmarolle and O'Brien map areas.[5] The largest is the Privat band which averages $\frac{1}{3}$–$\frac{3}{4}$ miles wide and extends southeast across the townships of Royal-Roussilon, Poularies, and Privat into Manneville township. The rocks are described as fine to coarse tuffaceous material. Similar but smaller bands are de-

[1] A. D. Coleman, "The Pre-Cambrian Rocks North of Lake Huron with Special Reference to the Sudbury Series," *Ont. Bur. Mines*, Vol. XXIII (1914), pp. 204–36.

[2] W. H. Collins, "North Shore of Lake Huron," *Geol. Surv. Can. Mem. 143* (1925), pp. 26–7.

[3] A. C. Lawson, "Some Huronian Problems," *Bull. Geol. Soc. Amer.*, Vol. XL (1929), pp. 371–79.

[4] H. C. Cooke, W. F. James, and J. B. Mawdsley, "Geology and Ore Deposits of Rouyn-Harricanaw Region, Quebec," *Geol. Surv. Can. Mem. 166* (1931). This memoir was published after this paper was submitted for publication. New information in the memoir made necessary certain changes in this paper.

[5] B. S. Buffam, "Keewatin Sediments of Palmarolle and O'Brien Map-Areas," *Can. Geol. Surv. Mem. 166* (1931), pp. 33–8.

scribed in each of the following townships: Languedoc, Guyenne, LaSarre, LaReine. Also a band of slate and phyllite about 2,000 feet wide extends at least $1\frac{1}{2}$ miles east from Duparquet Lake. South of Pelletier Lake, fine-grained tuffaceous sediment outcrops over a width of half a mile and a length of nine miles.[1] They are soft, dark gray to grayish black, and thinly banded.

In the LaMotte and Piedmont map-areas several bands of schists of sedimentary origin closely associated with the Keewatin volcanics have been mapped.[2] It was not definitely ascertained whether they occur conformably interbedded with the volcanics or whether they were deposited after the volcanic activity had ceased, with the possibility that they could be considered Temiskaming in age. Some similarity between these sediments and rocks on Grand Lake Victoria considered to be Grenville is pointed out.[3]

The Cléricy band of sediments of the Cléricy map-area Temiscaminque and Abitibi counties, Quebec, was early considered to be of the same general age as the Keewatin volcanics.[4] Structurally the sediments appear to coincide closely with the adjacent Keewatin volcanics. They form a continuous band stretching diagonally across the Cléricy map-area for a distance of 24 miles. The dips are very steep and the greatest recorded width of the band is $2\frac{1}{2}$ miles, in Cléricy township. The sediments are largely arkose with some greywacke and slate and minor bands of conglomerate. Other rocks of the map-area, in addition to the Keewatin volcanics and Cléricy band of sediments, are the Temiskaming sediments and a variety of intrusive rocks of several different ages. In a recent publication the Cléricy sediments are tentatively grouped with the Temiskaming because they are considered to differ in character from bodies of supposed Keewatin sediments and because the conglomerates appeared to contain material eroded from the Keewatin.[5]

[1] James, Cooke, and Mawdsley, *op. cit.*, p. 38.

[2] W. F. James and J. B. Mawdsley, "LaMotte and Fourniere Map Areas, Abitibi County, Quebec," *Geol. Surv. Can. Summ. Rept.*, Part C (1925), p. 61.

[3] *Geol. Surv. Can. Mem. 166*, p. 40.

[4] W. F. James and J. B. Mawdsley, "Cléricy and Kinojevis Map-Areas, Temiscaminque and Abitibi Counties, Quebec," *Geol. Surv. Can. Summ. Rept.*, Part C (1924), pp. 107–9.

[5] *Geol. Surv Can. Mem. 166*, p. 61.

DESMELOIZES AREA

Mawdsley[1] reports wide sedimentary bands in the Desmeloizes map area which conform in trend with the volcanics. In addition, many narrow sedimentary and tuffaceous beds occur interbedded with the volcanics in many parts of the area. The sediments consist largely of interbedded slates and impure sandstone or greywacke. The longest band, indicated by poor exposures, is about 12 miles long and averages about $\frac{3}{4}$ mile wide, but other scattered exposures of sediment probably representing a continuation of this band occur along its strike in the map area and for as much as 25 miles beyond.

The sediments appear to be in structural conformity with the volcanics and were mapped as Keewatin. Most of the sediments are thought by Mawdsley to lie at or near the top of the volcanic assemblage along the axis of synclinal folds which have involved the volcanics and the sediments.

SUDBURY AREA

The Ridout series of sediments as described in the Sudbury district, Ontario,[2] lies within the Keewatin volcanics. The sediments occur as small members interbedded with the volcanics and also as a wide band separating the volcanics into two major divisions. The series has been traced for 50 miles with no indication at either end that it does not continue beyond. Its least-known thickness appears to be 2,500 feet in Garnet township. From the map it appears several times thicker in Osway township where it attains its maximum known thickness. The series "is largely composed of greywacke and argillite, but conglomerate, arkose, and impure quartzite are prominent locally."

MICHIPICOTEN REGION[3]

The Keewatin volcanics are separated into two parts by the Dore series of sediments. These sediments conform in structure to the associated volcanics. They grade downward into the volcanics

[1] J. B. Mawdsley, "Desmeloizes Area, Abitibi District, Quebec," *Geol. Surv. Can. Summ. Rept.*, Part C (1928), pp. 38–46.

[2] R. C. Emmons and Ellis Thomson, "Woman River and Ridout Map Areas, Sudbury District, Ontario," *Geol. Surv. Can. Mem. 157* (1929), p. 7.

[3] W. H. Collins, T. T. Quirke, and Ellis Thomson, "Michipicoten Iron Ranges," *Geol. Surv. Can. Mem. 147* (1926).

through tuffaceous material. The contact with the overlying volcanics is sharper but does not appear to be unconformable. Two prominent bands of the Dore sediments are mapped in the map area. The southern one shows a maximum thickness of 8,400 feet and a minimum of only a few hundred feet. It extends into the area for about 15 miles. The greatest estimate of the thickness of the northern band is 2,800 feet. The composition of the sediments is as variable as their thickness. Conglomerates, greywackes, slates, mica schists, and tuff-like material are among the rock types making up the series. Many narrow bands of clastic sedimentary material occur interbanded with the post-Dorean Keewatin volcanics. They range from fine conglomerates to greywackes to slates.

NORTHWEST OF LAKE SUPERIOR

Sedimentary schists occur in the Rainy Lake district of Ontario, with regard to the stratigraphic position of which there has been much difference of opinion. The literature is extensive, and as the writer can add nothing to the discussion the occurrence will be only briefly mentioned. A thick series of sedimentary schists has been referred to the Coutchiching and held by some to be a series of considerable magnitude underlying the Keewatin.[1] Others are of the opinion that the bulk of the sedimentary schist at least is post-Keewatin[2] and suggest that any sedimentary material that may occur beneath the volcanics in this region is so small in amount that it should be included in the Keewatin with the volcanics. There appears at least a small amount of sedimentary schist interbedded with the volcanics of the Keewatin.

[1] A. C. Lawson, "Geology of Rainy Lake Re-studied," *Geol. Surv. Can. Mem. 40* (1913); T. L. Tanton, "Stratigraphy of the Northern Subprovince of the Lake Superior Region," *Bull. G. S. A.*, Vol. XXXVII (1927), pp. 731–48.

[2] E. F. Grout, "Coutchiching Problem," *Bull. G. S. A.*, Vol. XXXVI (1925), pp. 351–64; J. E. Hawley, "Seine or Coutchiching," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 521–47.

THE BASALTS OF PATAGONIA

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ABSTRACT

The basalts of Patagonia, as determined from the literature and from the microscopical and chemical study of rocks from three widely separated localities, are found to belong to those slightly undersaturated types which appear to be characteristic of plateau-basalts in the restricted sense of Gregory and Reck. This type contrasts with that of flood-basalts which, in general, are oversaturated with silica.

In pursuance of research into the nature of basalts, especially those which are poured out in great quantity over wide areas of country, the writer requested Dr. W. R. Smellie, M.A., of the Anglo-Persian Oil Company in Argentina, to procure for him some samples of the Patagonian "plateau-basalts" of Kainozoic age. In response to this appeal Dr. Smellie kindly sent hand-specimens, respectively, from the region south of Lago Buenos Aires (Lat. 46° 30′ S., Long. 72° W.); the Cerro Gaucho, 15 miles south of Las Heras (Lat. 47° S., Long. 69° 50′ W.); and the Sierra Chaira, 30 miles north of Pico Oneto, near Lake Colhui Huapi (Lat. 45° 30′ S., Long. 68° 30′ W.). These rocks have been subjected to microscopical examination, and a chemical analysis of a rock from Lago Buenos Aires has been made (Table I, 1).

The great basalt lava fields of Patagonia rest upon flat-lying Kainozoic sediments (Eocene to Pleistocene), of which the vast extra-Andine plains or pampas are composed. The basalts form extensive flat-topped plateaus or mesetas, which, on Quensel's map,[1] cover five large areas to the south of Lago Buenos Aires, and two smaller areas to the north of that lake. On this map the basalt is shown as covering an area of about 11,000 square miles to the south of Lago Buenos Aires, but Quensel's work was confined mainly to the cordilleran region of Patagonia, and the eastern boundaries of the basalt plateaus are left rather vague. From the fact that Dr. Smellie has collected a basalt from near Lago Colhui Huapo, at least 70 miles farther east than the eastern boundary of Quensel's

[1] P. D. Quensel, "Geol.-petr. Studien in der Patagonischen Cordillera," *Bull. Geol. Inst. Upsala*, Vol. XI (1911), Pl. V, pp. 1–114.

nearest mapped basalt plateau, and that J. B. Hatcher[1] describes the basalt region in the neighborhood of the Rio Santa Cruz as having an average width of 100 miles, we may venture at least to double the above-mentioned figure, and state that the Patagonian basalts, so far as known, cover an area of about 25,000 square miles.

According to Hatcher, the sources of the flows are a series of small plugs and craters which "are most numerous over an area of about 40 miles in breadth, extending across the country from north to south, distant about 80 to 120 miles from the mountains [the Andes]."[2] The great basalt mesetas lie to the west of this zone of vents, between it and the Andes. Another extensive group of plugs and craters occurs near the mouth and at the headwaters regions of the Gallegos River,[3] but apparently these are not connected with lava fields.[4] Hatcher also speaks of a dike, 15–20 feet thick, which pierces the stratified Tertiary sediments in the Rio Chico Valley. He "traced this dike for many miles and found it outcropping wherever the surface of the stratified rocks was not covered over with shingle, thus demonstrating that the covering of shingle was deposited long after the lavas from this fissure had been poured out over the plain."[5] He thus apparently believed in fissure eruption as an additional mode of origin of the Patagonian basalts. He says further:

> Considering the number and size of these dikes and volcanoes it does not seem necessary to look farther for the origin of the basalts. And when one travels over the basalt-covered region, it becomes evident that they do not consist of one great sheet, which has flowed out and over a comparatively uniform and gently-sloping surface. There were, on the contrary, many flows from quite different sources, and the various streams were spread over an already deeply-eroded surface.

Hatcher may also have observed some sills, for he speaks of a highly columnar basalt, 50 feet thick, intercalated between Cre-

[1] *Reports of the Princeton University Expedition to Patagonia, 1896–99*, Vol. I (1903), p. 219.

[2] "Geology of Southern Patagonia," *Amer. Jour. Sci.*, Vol. IV, No. 4 (1897), p. 350.

[3] Hatcher, *ibid.*, and Quensel's map.

[4] H. Steffen, *Westpatagonien*, Vol. II (1919), pp. 58, 626.

[5] *Reports of the Princeton University Expedition to Patagonia, 1896–99*, Vol. I (1903), p. 220.

taceous and Tertiary sediments (apparently the Patagonian formation—Oligocene to Miocene) in the region about Lake Pueyrredon (Lat. 47°30′ S.).

Charles Darwin provided the first detailed account of the pampa basalts;[1] but as he boated up the Santa Cruz River, encountering immense difficulties on the way, he saw only the great basalt sheets, and missed the volcanic vents of the plateaus between the rivers. Hence he thought that the "vast deluges of basaltic lava" had come from the cordilleran volcanoes to the west.

In a communication to O. Bäckström,[2] P. D. Quensel pointed out that in the western parts of the mesetas there were many raised basalt blocks that appeared to be bounded by fractures; and it appeared to him probable that these "basalt horsts" represented the central foci of the igneous activity from which the basalt streams had flowed quietly over the surrounding lower country. Tuffaceous material played only a subordinate part in the building-up of the mesetas. Quensel thus appears to have had in view central basalt domes of Hawaiian or Icelandic type as the sources of the flows.

The Patagonian basalt sheets are mostly intercalated with sediments of the Santa Cruz formation (Miocene); and, in general, the eruptions had ceased before the oncoming of the Glacial period. There are flows, however, especially in the southern part of the region, which overlie the Quaternary gravels, and which were certainly erupted after the initiation of the present valley system.

Entirely analogous basaltic lavas, tuffs, and vents occur within the eastern plateau region of Graham Land, West Antarctica.[3] North of the Patagonian region Quensel's map shows pampa basalts just east of the Andean line in Lat. 45° S. and Lat. 41° S. H. G. Backlund has recorded pampa basalts in the southern part of Mendoza, Argentina, east of Cerro Payen (Lat. 37° S.).[4] He regards

[1] *Geological Observations on South America* (London, 1846), p. 115 ff.

[2] "Petrographische Beschreibung einiger Basalte von Patagonien, West-Antarktika. und den Süd-Sandwich Inseln," *Bull. Geol. Inst. Upsala*, Vol. XIII (1915), pp. 115–82.

[3] J. G. Andersson, "On the Geology of Graham Land," *Bull. Geol. Inst. Upsala*, Vol. VII (1906), pp. 19–71; O. Nordenskjöld, "Antarctis," *Handb. d. Reg. Geol.*, Vol. VIII, Part 6 (1913), p. 4.

[4] "Der magmatische Anteil der Cordillera von Süd-Mendoza," *Medd. Abo Akad. Geol.-Min. Inst.*, No. 3 (1923), p. 256.

them, together with the Patagonian basalts, as connected with the latest phase of the cordilleran orogeny.

PETROGRAPHY

O. Bäckström has given the most comprehensive account of the petrography of Patagonian basalts.[1] He has fully described specimens from the basalt plugs of the Los Frailes region south of the Rio Gallegos in Southern Patagonia, from the Sierra de los Baguales south of the Rio Santa Cruz, and from the basalt mesetas northward from Lago Argentino. By far the greater number of the rocks described are porphyritic olivine-basalts of the types hereinafter described; but from the Sierra de los Baguales, rocks are described which carry numerous large phenocrysts of labradorite, and thus resemble the "navites" of Germany, and the Markle basalts of Scotland. Hypersthene-andesite has also been obtained from the upper reaches of the Rio Baguales in the neighborhood of the watershed at a height of 1,000 meters; but as here the andesite lavas of the Eastern Cordilleras and the extra-Andine basalt mesetas come into rather close proximity, whereas at all other localities they are widely separated, the view may be taken that, in this locality, there is intermingling of the products of two different igneous fields.

Apart from a few casual notes by Quensel and Backlund in the papers cited above, the only other petrographic reference to Patagonian basalts is by Dr. H. S. Washington.[2] Unfortunately the provenance of the specimen analyzed by Dr. Washington is doubtful (see p. 379 of this paper). It is a feldspar-basalt with a considerable amount of brownish interstitial glass and some partially serpentinized and corroded olivine.

The rock from south of Lago Buenos Aires which has been analyzed (Table I, 1) is a dark gray, compact basalt with a few, small, inconspicuous phenocysts of plagioclase and of olivine. The other two rocks are coarser and do not exhibit any phenocrysts. In thin section the analyzed rock shows small euhedral phenocrysts of plagioclase, and glomeroporphyritic clumps of olivine and augite

[1] *Op. cit.*, pp. 126–45.

[2] "Deccan Traps and Other Plateau Basalts," *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 795.

crystals, besides isolated crystals of the same minerals, embedded in a groundmass of which the most conspicuous elements are plagioclase laths in sub-parallel arrangement. The other elements of the holocrystalline groundmass are grains of augite and magnetite, and a base of colorless anisotropic material which seems to be of feldspathic character.[1] The plagioclase, which is highly zonal, appears to be labradorite about Ab_1An_1, but which may pass to oligoclase on the margins of the crystals. A few of the larger crystals seem to consist entirely of oligoclase (extinction, 5°), and possess cores full of glassy and mineral inclusions. The olivine is colorless, euhedral, and fresh, or at most shows an incipient alteration to a pale green serpentine. The augite is mostly euhedral; it is of a pale brown color, and shows only a faint trace of violet in a few of the sections. The olivine and augite take part in small glomeroporphyritic aggregates with which one or two of the larger feldspars are associated. An interesting feature of one of these aggregates is that the adjacent lathy feldspars of the groundmass are arranged tangentially around it, forming a kind of ocellar structure.

The rock from the Sierra Chaira is considerably coarser than the above, and the feldspars and augite of the groundmass possess a well-marked ophitic texture. The augite is definitely purple and does not occur as phenocrysts. Olivine is the only porphyritic mineral, and is largely altered to a reddish serpentine. The rock is full of minute, irregular steam cavities into which secondary carbonates have infiltrated.

The basalt from the Cerro Gaucho is the most basic of the three. Its texture is intermediate in size between those of the other two rocks under description, being coarser than that of Lago Buenos Aires, but still of intergranular type—not so coarse as that of Sierra Chaira, and not ophitic. The augite is of a definitely purple tint, and the olivine occurs in fresh, more or less rounded grains which are aggregated into small groups. The olivine is so abundant that this rock represents a transitional type between ordinary olivine-basalt and the richly olivinic type known as oceanite. There is in this rock, as in the analyzed specimen, a very small amount of obscurely

[1] This may be anemousite. See Barth, *Jour. Wash. Acad. Sci.*, Vol. XX (1930), pp. 60–68.

polarizing, colorless base, apparently of feldspathic or feldspathoidal character.

CHEMICAL COMPOSITION

An analysis of the rock from Lago Buenos Aires has been made by Mr. Herdsman, and is set out in Table I, 1, along with analyses

TABLE I

ANALYSES OF PATAGONIAN BASALTS, ETC.

	A	1	B	2	C
SiO_2	48.97	45.25	45.18	48.36	49.82
Al_2O_3	16.12	16.47	14.69	12.01	13.38
Fe_2O_3	1.90	2.44	1.94	4.56	4.18
FeO	9.63	8.69	8.91	6.91	9.69
MgO	7.64	7.77	8.98	8.58	5.61
CaO	8.73	8.90	9.36	8.48	9.89
Na_2O	2.99	2.68	3.14	2.47	2.22
K_2O	1.21	1.42	.94	.69	1.12
H_2O+	1.39	1.60	3.80	2.76	1.29
H_2O-		.70	.81	1.46	1.00
TiO_2	1.62	3.20	2.00	2.60	2.20
P_2O_5	.....	.43	.35	.35	.29
MnO	tr.	.38	.16	.30	.18
(Ni, Co)O	.....	nil	.....	.....	.....
S	.....	nil	.20	.....	.....
CO_2	.....	nil	.32	.....	.....
BaO	.....	.....	.05	.....	.....
	100.20	99.93	100.83	99.53	100.87

A. Olivine-basalt, Cockburn Island, Graham Land (analysis by Prior). Quoted from G. T. Prior, *Miner. Mag.*, Vol. XII (1900), p. 89.

1. Olivine-basalt, Lago Buenos Aires, Argentina. Plateau basalt of Late Kainozoic age (analysis by Herdsman). New analysis.

B. Essexite-gabbro of teschenitic affinity, confluence of Rio Mayer with Rio Pinto, Patagonia (analysis by Mauzelius). Quoted from P. D. Quensel, *Bull. Geol. Inst. Upsala*, Vol. XI (1911), p. 74.

2. Basalt, Patagonia (analysis by Washington). Quoted from H. S. Washington, *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 794.

C. Fine-grained dolerite, from "Gondwana Formation," between Puerto Aguirre and the cataract of Iguazu, Uruguay. Quoted from K. Walther, *Inst. Geol. Perforac., Montevideo, Bull. No. 9* (1927), pp. 41.

of the Patagonian basalt described by Washington; the olivine-basalt from Cockburn Island which, in all probability, represents the continuation of the Patagonian basalt plateau in West Antarctica; the essexite-gabbro or teschenite of the Andean foothills in Patagonia described by Quensel; and a fine-grained dolerite from

Uruguay, which belongs to the Gondwana igneous episode of South America.

The Lago Buenos Aires analysis is that of an undersaturated olivine-basalt of a type which is common in most plateau-basalt fields.[1] Its norm (Table II, 1) shows over 17 per cent of olivine, and even a little nepheline. It is undersaturated to the extent of 118 "molecules" of silica, and its "silica number" is therefore −118.[2] The closest local analogue of this rock is undoubtedly the olivine-basalt from Cockburn Island (Table I, A), notwithstanding its higher silica. Its norm shows 15.6 per cent of olivine, but no nepheline, and its symbols in the C.I.P.W. classification are practically the same as those of the Patagonian rock. Its silica number is −96. Another closely comparable rock, as regards its chemistry, is the essexite-gabbro or teschenite from Patagonia described by Quensel. This intrusion occurs in the foothills of the Andes only a few miles west of the great basalt plateau lying between the Rio Chico and the Rio Shehuen; and while the alkaline intrusions of the sub-Andine region, as far as the evidence goes, appear to be somewhat older than the basalts, their distribution and petrographic characters support the view that they represent an early hypabyssal phase of the Patagonian plateau basalts. The tabulated analysis by Mauzelius (Table I, B) is very close to that of the analyzed basalt in essentials. Its alumina is lower, and its soda-potash ratio higher, than in the Patagonian basalt. Its norm, however, works out very similar to that of the basalt, and it has a silica number of −163.

Very different from these three analyses is Washington's analysis of a basalt from "Patagonia." The provenance of this specimen is at least doubtful, as Washington himself recognizes. It was collected by Ameghino, and was stated to have come from *la base des couches à "Notostylops,"* which are of Eocene age. No definite locality was noted on the label of the specimen. Hatcher's frequent strictures[3] on Ameghino's haphazard collecting and careless localization of his

[1] Compare, for example, those of Transjordania (G. W. Tyrrell, *Geol. Mag.*, Vol. LXVII (1930), p. 413).

[2] F. F. Grout, *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 620; G. W. Tyrrell, "Petrography of Jan Mayen," *Trans. Roy. Soc. Edin.*, Vol. LIV, Part 3 (1926), p. 762.

[3] *Amer. Jour. Sci.*, Vol. IX, No. 4 (1900), pp. 87, 91, 103.

fossil specimens indicate that little or no reliance can be placed on the authenticity of Washington's specimen. This view is strengthened by the great differences between the analysis of this rock and those above cited. It is an oversaturated basalt which, however, contains a little residual olivine. Its chief chemical differences to the olivine-basalt of Lago Buenos Aires are its increased silica and diminished alumina, which result in quartz appearing in the norm.

TABLE II

NORMS*

	A	1	B	2	C
Quartz	.....	.....	.....	3.24	4.26
Orthoclase	7.23	8.34	5.56	3.89	6.67
Albite	25.15	22.01	21.22	20.96	18.34
Anorthite	26.97	28.63	23.07	19.74	23.35
Nepheline	.....	.57	2.98	.....	.....
Diopside	13.41	10.36	15.98	16.23	19.40
Hypersthene	4.68	.....	.....	18.90	15.33
Olivine	15.62	17.32	19.12	.....	.....
Magnetite	2.78	3.48	2.78	6.50	6.03
Ilmenite	3.04	6.08	3.80	5.02	4.26
Apatite	.....	1.01	.68	.68	.68
Calcite	.....	.....	.70	.....	.....
Silica number	−96	−118	−163	54	71

The symbols of these analyses in the C.I.P.W. classification are as follows:

A	(II) III.	5.	3 (4).	4.
1	(II) III.	5.	(3) 4.	4.
B	III.	5.	3″.	4″.
2	III.	″5.	3 (4).	4 (5).
C	III.	″5.	(3) 4.	4.

*The order of the analyses is the same as in Table I.

The silica number is thus positive, and amounts to 54. This analysis is closely comparable to those of the similar oversaturated basalts of the Deccan, and to those of the Gondwana formation in South America. It is particularly close to that of an Uruguayan example which is tabulated for comparison (Table I, C), the norm and C.I.P.W. symbols being also closely comparable (Table II). It is perhaps not straining probabilities to suggest that some specimens of Gondwana basalts and dolerites had become mingled with Ameghino's Patagonian basalts, and that Washington's analysis really refers to a Gondwana lava, which is, according to Walther's

numerous analyses, invariably oversaturated. While it cannot be denied that oversaturated basalts may occur in the lavas of the Patagonian mesetas, yet the published descriptions by Bäckström and Backlund and the descriptions given in the present paper are definitely against the probability of their occurrence.

Are the Patagonian basalts flood eruptions or plateau eruptions? A word of explanation of the terms "flood eruption" and "flood-basalts" is perhaps necessary. The writer uses these terms for enormous regions of lava flows, overwhelmingly composed of basalt, such as those of the Deccan, the Columbia region of the Northwestern United States, and of the North Atlantic, in which the topographic features of the overflowed region have been swamped by lava as by a flood. In review of the relative scarcity of volcanic vents and fragmental products of explosion in these vast fields, it is assumed that the fissure mode of eruption has given rise to the major part of the flows.[1] Following Professor J. W. Gregory[2] the writer applies the terms "plateau eruption" and "plateau-basalts" to volcanic outbursts which occupy much smaller areas than flood eruptions, and which have been extruded from numbers of closely spaced central volcanoes. These, too, are mainly composed of basalt, which is usually olivine-bearing and somewhat alkalic. Typical examples are the lava fields of East Africa, Victoria, and the early Carboniferous basalt plateaus of the Midland Valley of Scotland. Professor H. Reck[3] has recently renamed this type as "areal eruption," although the same term has been used by F. von Wolff[4] to designate Daly's type of "eruption by local foundering" of the roof of a batholith.

From the facts given in the earlier part of this paper it seems clear that the Patagonian basalts have been erupted mainly from a series of small vents and craters which occur in a zone extending north and south along the eastern margin of the basalt plateaus, and

[1] G. W. Tyrrell, *Volcanoes* (Home University Library, 1931), pp. 190–98, and Fig. 27, p. 206; but see J. W. Gregory, *Earthquakes and Volcanoes* (Benn's Sixpenny Library, 1929), pp. 34–37, for arguments against fissure eruption.

[2] J. W. Gregory, *op. cit.*, p. 37, and *The Great Rift Valley* (1896), p. 219.

[3] "Die Masseneruptionen unter besonderer Würdigung der Arealeruption in ihrer systematischen und genetischen Bedeutung für das islandische Basaltdeckengebirge," *Deutsche Island-Forschung* (1930), pp. 24–49.

[4] *Vulkanismus* (1914), p. 435.

are therefore plateau eruptions (Gregory) or areal eruptions (Reck). This, however, does not exclude the possibility of the occurrence of great shield volcanoes (Quensel, see p. 376), or of fissure eruptions (Hatcher, see p. 375). The whole question of the mode of origin of the Patagonian basalts, and of the great basalt fields of the world in general, needs much further study.

The results of the present study help to confirm the view that plateau-basalts in general are undersaturated, in contrast to flood basalts, which are as a rule oversaturated rocks. The hypabyssal representatives of flood basalts are great sill swarms and dike swarms consisting mainly of quartz-dolerite, and their plutonic representatives are the quartz-gabbro lopoliths. On the other hand, alkali-dolerites of various kinds, essexites, and teschenites are the coarse-grained representatives of plateau-basalts.

REVIEWS

The Fauna of the Drum Limestone of Kansas and Western Missouri. By ALBERT NELSON SAYRE. "University of Kansas Science Bulletins," Vol. XIX, No. 8, 1930 (1931). Pp. 75–203; pls. 21.

The Drum limestone is an oölitic member of the Kansas City formation of the Pennsylvanian series. Although its prolific (in the Kansas City area, dwarfed) fauna has attracted the attention of many paleontologists, it remained for Dr. Sayre to prepare the first detailed paleontologic report upon it.

The faunal assemblage comprises 70 genera and 131 species, of which 33 are described as new. Although all the important groups of invertebrates are represented, the fauna is dominantly molluscan. Sayre's 21 plates adequately illustrate this interesting invertebrate assemblage, and his descriptions are well done. His policy of making dwarf forms conspecific with the normal-sized individuals, in so far as possible, is to be commended, particularly in view of the modern tendency toward multiplication of species. Students of sedimentation and stratigraphers, however, may miss the detailed sections, correlation charts, and faunal tables which might well have been added to the report.

CAREY CRONEIS

The Microscopic Characters of Artificial Inorganic Solid Substances or Artificial Minerals. By A. N. WINCHELL. New York: Wiley & Sons, 1931. Pp. 403; figs. 310. $5.00.

This is the second edition of *The Optic and Microscopic Characters of Artificial Minerals* published by the University of Wisconsin in 1927. The first 150 pages are devoted to "Principles and Methods." This section, which was absent from the first edition, consists of a revision of the authors well-known *Elements of Optical Mineralogy*, Part I, omitting chapters iv, x, xii, xiv, xv, xviii, and xix, together with a chapter on "The Universal Stage" by Professor R. C. Emmons. In the next 190 pages are given, in thoroughly revised form with many additions, "Descriptions of Artificial Inorganic Solid Substances"; the same chemical-valence form of classification is retained. Part III, "Determinative Tables," is not greatly changed from the old edition except for corrections and additions; but a column to show dispersion is a new feature, and maximum birefringence is omitted in favor of giving the third index of refraction of biaxial minerals. The book should be of great value to those working with artificial inorganic crystals and glasses.

D. J. FISHER